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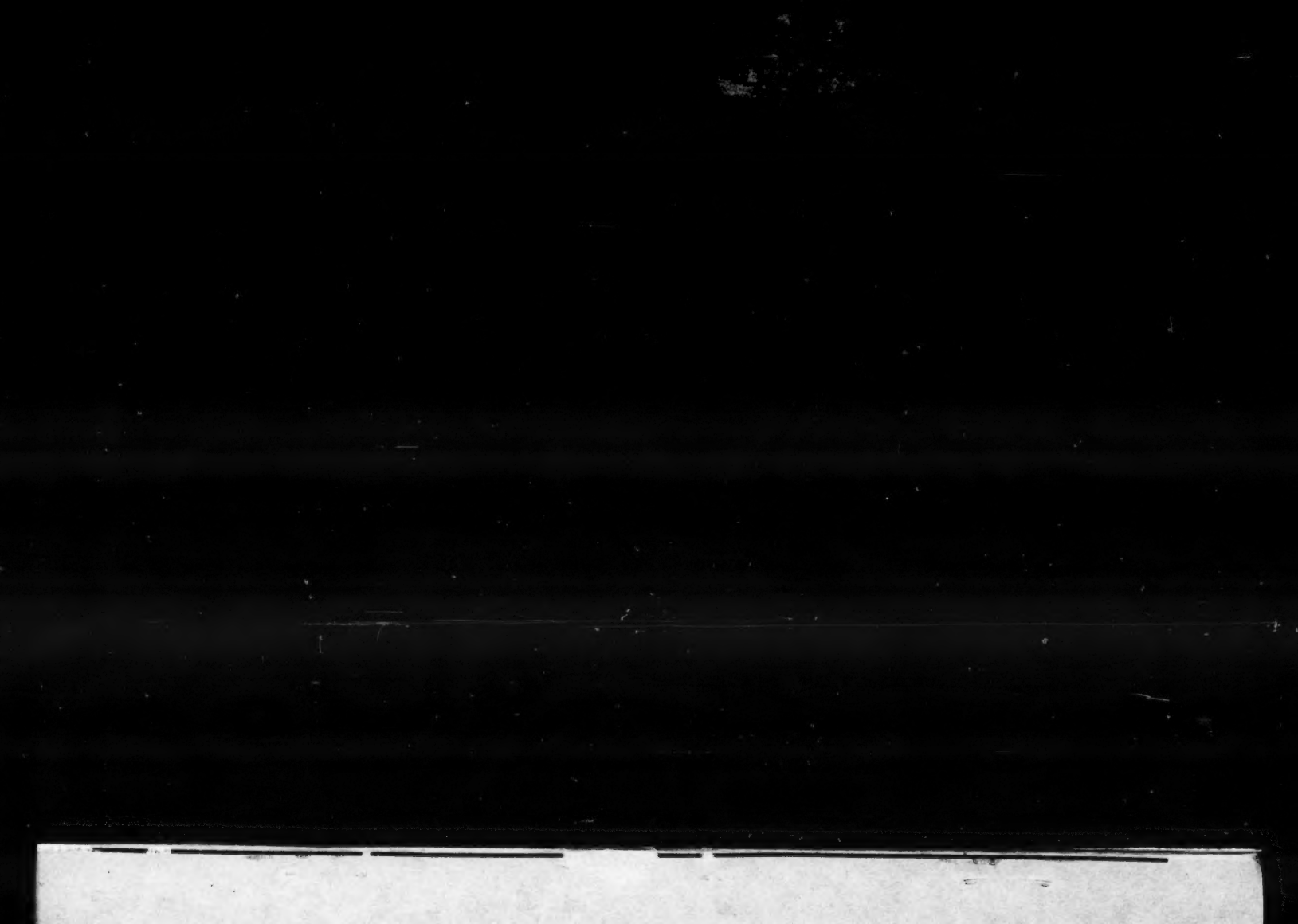

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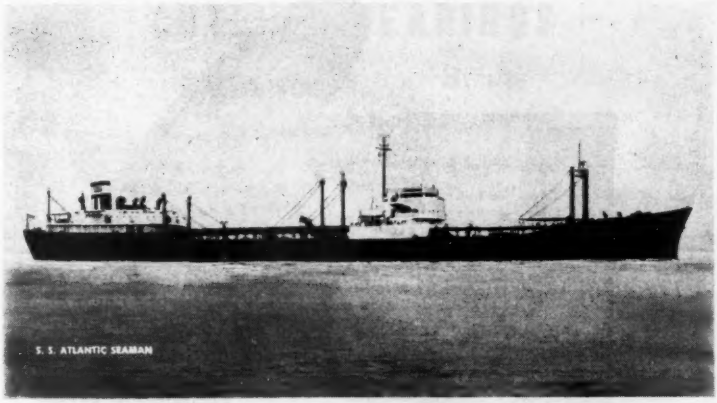


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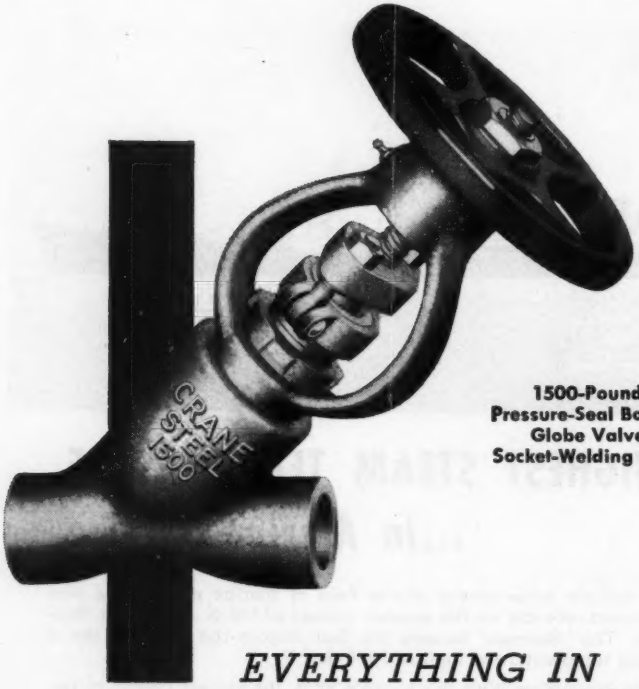


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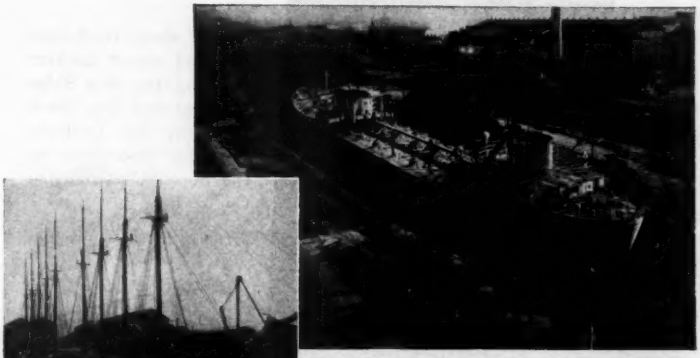

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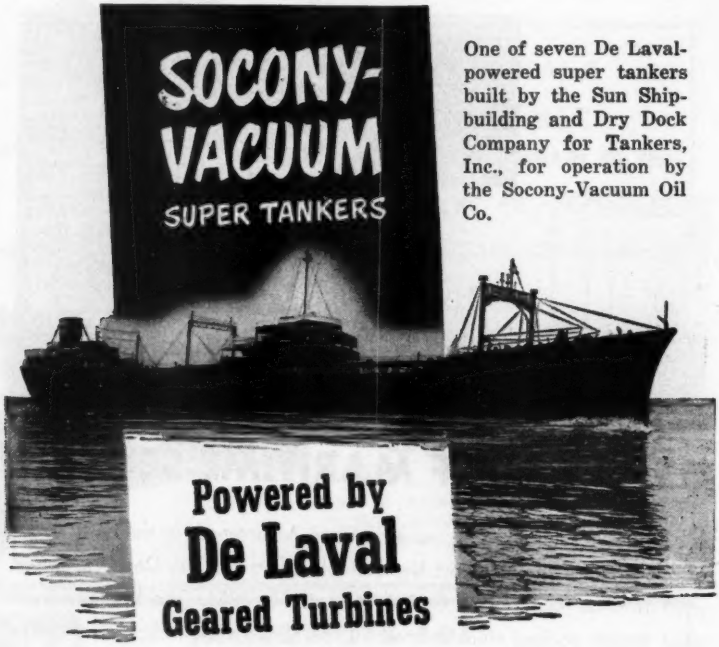


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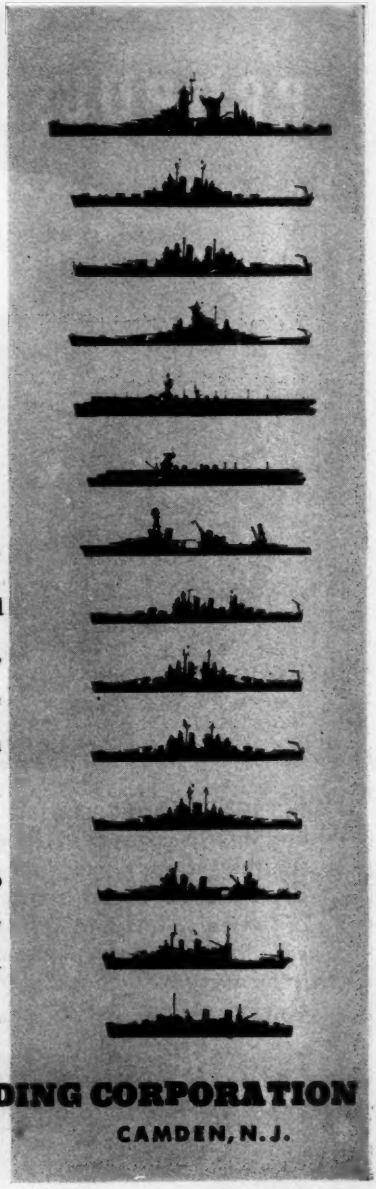

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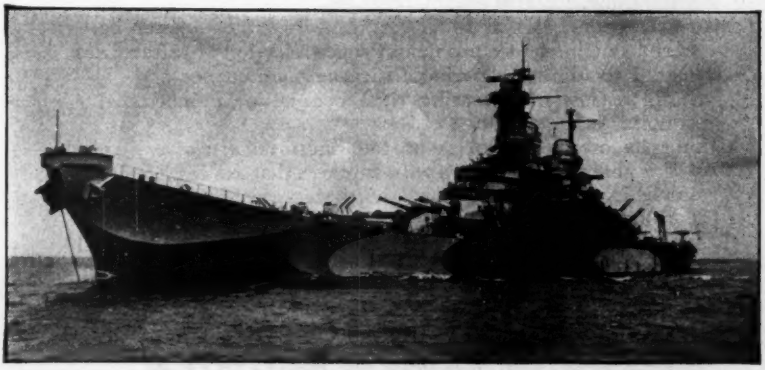

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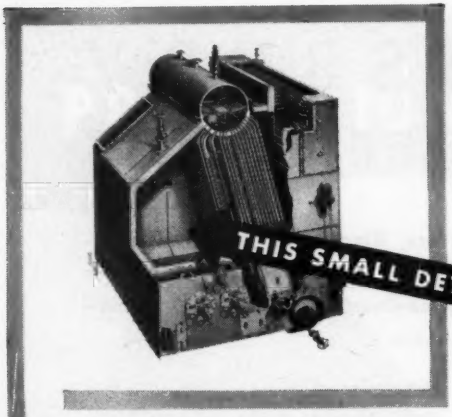

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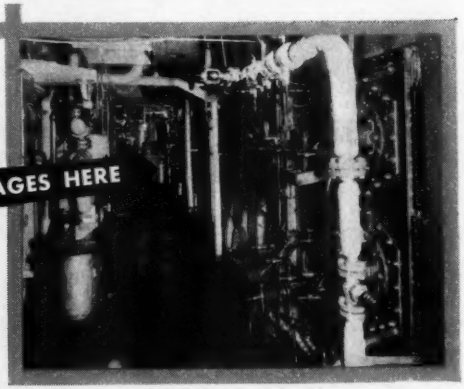

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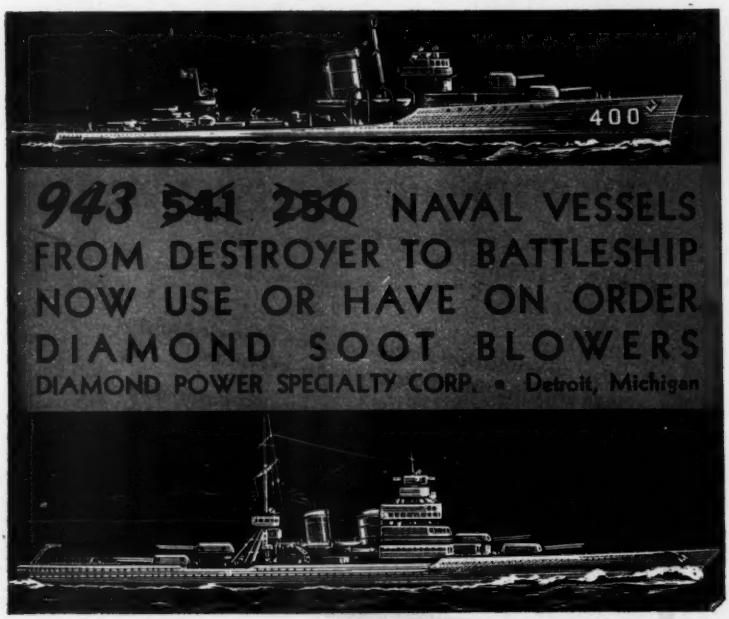
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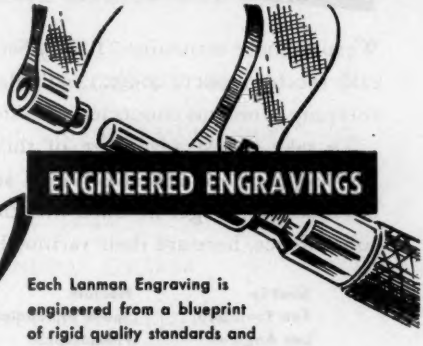

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# SPECIAL NOTICE

THE ANNUAL BANQUET OF THE SOCIETY

WILL BE HELD AT

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IN WASHINGTON, D. C.

ON

**FRIDAY, 27 APRIL 1951**

THE PRESIDENT OF THE SOCIETY WILL PRESIDE

REAR ADMIRAL W. D. LEGGETT, JR., U. S. N.

DEPUTY CHIEF OF THE BUREAU OF SHIPS

WILL ACT AS TOASTMASTER

THE PRINCIPAL SPEAKER

HAS NOT YET BEEN SELECTED

**Official U. S. Navy Photograph.**

REAR ADMIRAL DAVID H. CLARK, U. S. NAVY, Chief of the Bureau of Ships. President of the Society for 1951.

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# JOURNAL

OF

# THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

VOL. 63. FEBRUARY 1951. No. 1



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The Society as a body is not responsible for statements made by individual members



COUNCIL OF THE SOCIETY

(Under whose supervision this number is published).

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Captain J. E. HAMILTON, U.S.N., Secretary-Treasurer


## SECRETARY'S NOTES

### 1950 ELECTIONS

The Officers of the Society who will serve during 1951 as a result of the 1950 election and carryovers are:

*President:* Rear Admiral D. H. Clark, U.S.N., Elected

*Secretary-Treasurer:* Captain J. E. Hamilton, U.S.N., Elected

*Council:* Regular Navy: Captain W. A. Dolan, U.S.N., Elected

Rear Admiral Louis Dreller, U.S.N., Continued

Captain C. M. Tooke, U.S.N., Continued

Captain F. W. Walton, U.S.N., Elected

Naval Reserve: Commander C. H. Campbell, U.S.N.R., Elected

Captain W. M. Tann, U.S.N.R., Continued

Coast Guard: Captain R. A. Smyth, U.S.C.G., Continued

Civilian: Mr. Francis H. Engel, Continued

Mr. John C. Niedermaier, Elected

The Proposed amendment to the By-Laws was approved by vote of the Society whereby the following officials were added to those who, are ex-officio, honorary members of the Society during their incombencies:

The Under Secretary of the Navy

The Assistant Secretary of the Navy for Air

The Chief of Naval Material

The Chief of Naval Research

The Deputy Chief of the Bureau of Ships

### Changes in Council

The sincere thanks of the Society are due to the retiring President, Rear Admiral F. E. Haeberle, U.S.N., and to those members of the Council whose terms expired on 31 December 1950, namely:

Captain T. T. Dantzler, U.S.N.

Rear Admiral T. C. Lonnquest, U.S.N.

Lieut. Commander Nicholas Tiedeman, U.S.N.R.

Mr. R. M. Wilson

### Annual Banquet

The annual banquet of the Society, as is customary, will be held on the last Friday in April—27 April 1951. As in the past, this year's banquet will be held at the Statler Hotel in Washington, D. C. Arrangements will be similar to those of previous years. There is every reason to expect that the great success of past years will be repeated.

One non-member guest for each member *who attends* will be permitted. If, however, applications exceed the capacity of the hotel, it will be necessary for the banquet committee to make adjustments. The price remains unchanged — $10.00 for members and $12.50 for non-members.

The principal speaker for the banquet has not yet been selected. Rear Admiral W. D. Leggett, Jr., U.S.N., Deputy Chief of the Bureau of Ships, will officiate as Toastmaster.

Although the Council has decided to go ahead with plans for the banquet, the possibility that emergency or international developments may force cancellation can not be completely neglected. We sincerely hope that this will not happen and intend to proceed on the assumption that it will not.

Forms for application for seats, with detailed information, will be placed in the mails in the near future.

## Membership

The provision of the By-Laws which requires that members who become delinquent for two years be dropped resulted in a large reduction of membership — a total of 223. Each has been notified, with an invitation to reinstate himself. It is to be hoped that many of them will do so and that new members during the year will more than offset those lost.

## Volume 63 of Journal

The beginning of a new year, the Society's 63d, cannot help but recall the origin of the Society and the reasons for its continuance. The group of naval engineers who founded the Society in 1888 were among those graduates of the U.S. Naval Academy who had followed the engineering curriculum there. This same source has provided the country with a considerable number of engineers whose influence was extended far beyond the Navy. These included such outstanding educators as Hollis ('78) of Harvard, Cooley ('78) of Michigan and Durant ('80) of Stanford.

When it is recalled that, when the Society of Civil Engineers was founded in 1852, there were only two kinds of Engineers — Civil and Military, the importance of the action of these *Naval* engineers, only 36 years later, can be appreciated. Machinery in the Navy had assumed great importance with the beginning of Naval construction in 1883. Continuation of shipbuilding and rapid strides in general engineering outside the Navy pointed up the need for a medium to foster the application of engineering advances to naval purposes and to stimulate independent advances in the art. This, of course, was before the addition of electricity,

electronics and internal combustion engines. In retrospect engineering in the Navy was simple and elementary, but for the time, it was far from that. Mechanics, rather than true engineering, exercised considerable influence. Theories, tested and available for application to new naval needs, were very few and for the most part yet to be developed. It was recognition of the need for this kind of development and for its promulgation which motivated our founders. Hence the JOURNAL.

The JOURNAL is still available for the same purpose. In these days of uncertainty and of international unease, our members who are providing the developments for the future operate under a cloak of national security. Most of the fruits of their work cannot be publicly divulged until after a considerable delay. By that time their authors are so burdened with new classified projects that they cannot find time for describing their earlier ones.

Some readers of the JOURNAL may have wondered why our pages have been opened to many papers of a nature whose connection with Naval Engineering is, at least, tenuous. We have described this in part previously. Regardless of how one defines "Naval Engineering", the current *task* of naval engineers has become so diverse that knowledge of many seemingly extraneous subjects if of interest, or even value, to them. In the absence of that valuable source of papers which security denies to us, our policy has been set so as to permit acceptance of the type of papers which are published.

The Council would be very happy to receive comments on this matter from any member. Absence of such comments can only lead to the assurance that our policy is acceptable.

### ASSISTANT SECRETARY

Change of duty which is impending has deprived the Secretary-Treasurer of the valuable services of Commander Frank C. Jones, U.S.N. Commander Jones has carried a large share of the burden of preparing the JOURNAL in his capacity as Assistant Secretary and Assistant Editor. In accordance with the By-Laws, the Council has appointed Commander Robert B. Madden, U.S.N., Assistant Secretary as of 1 January 1951.

### MR. DONALD L. HERR

It is gratifying to learn that Mr. Donald L. Herr, who became an Honorary Member of the Society by writing a prize essay, was

the recipient of one of the A. Cressy Morrison prizes for 1950, awarded by the New York Academy of Sciences. The prize was conferred for his paper on "A Theorem in Electromagnetism, with Useful Application to Computing Devices."

## ASNE IN 1898

The photograph which is reproduced on page 10 was discovered among the archives of the Society. It appears to be a picture taken of members who attended the Annual Meeting in 1898, the Society's tenth birthday. There should still be a few among us who recall some of the Spanish American War members.

*Front Row:* Capt. F. W. Walton, USN, 1951-52 Council; Capt. W. M. Tann, USNR, 1950-51, Council; Rear Adm. T. C. Lonnquest, USN, 1950 Council; Rear Adm. D. H. Clark, USN, 1951 President; Rear Adm. F. E. Haeberle, USN, 1950, President; Rear Adm. Louis Dreller, USN, 1950-51, Council; Mr. J. C. Niedermaier, 1951-52, Council; Mr. A. G. Fessenden, Clerk. *Back row:* Com. Nicholas Tiedeman, USNR, 1949-50 Council; Com. R. B. Madden, USN, 1951, Asst. Secretary; Capt. J. E. Hamilton, USN, Secretary-Treasurer; Capt. R. A. Smyth, USCG, 1950-51, Council; Capt. W. A. Dolan, Jr., USN, 1951-52, Council; Capt. C. M. Tooke, USN, 1950-51, Council; Com. F. C. Jones, USN, 1950, Asst. Secretary; Capt. T. T. Dantzler, USN, 1949-50, Council; Mr. F. H. Engel, 1950-51, Council; Mr. R. M. Wilson, 1949-50, Council. *Absent:* Com. C. H. Campbell, USNR, 1951-52, Council.

# PART ONE

## ORIGINAL ARTICLES

The articles which the Editor, acting under the supervision of the Council, has accepted for publication in Part One are the original works of the authors.

They are offered in furtherance of the Society's raison d'etre: to further the advancement of naval engineering. Discussion of any article is invited for publication in a subsequent issue.

Permission to reprint is freely granted on condition that *full acknowledgment is given* to the author and to the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS.

All articles which have been written by naval personnel or by civilian employes of the Navy Department and are published herein carry the personal view of the authors and, unless specifically so stated, do not express the official views of the Navy Department.

A. S. N. E. 1898

A. B. Canaga, C. A. Wheeler, J. B. Edson, Chas. E. Delaney, K. MacAlpine, John Platt, C. A. E. King, Jones, W. W. Wachsman, Harry Webster, W. M. McFarland, E. M. Janssen, Charles Ward, J. C. Kafer, Boyington, M. E. Reed, F. C. Bieg, Emil Theiss, J. G. Cristopher, B. C. Byran, W. W. White, Geo. W. Baird, L. O. S. Resizcky.

# PLANNING AND SCHEDULING A CV33 CLASS AIRCRAFT CARRIER AT A NAVAL SHIPYARD*

DR. GERALD PAUL STONE

THE AUTHOR

DR. STONE has been a civilian employee of the Navy Department since 1941. Among the positions he has held are Marine Engineer, Philadelphia Naval Shipyard and Naval Architect, Assistant for Production, and Industrial Engineer, New York Naval Shipyard. He is now the civilian supervisor of the Planning Office, Naval Supply Depot, Bayonne, New Jersey. During World War II, Dr. Stone worked with the New Construction Planning and Scheduling Group at the New York Naval Shipyard on the CV33 class. After war he continued his research and wrote his thesis on this subject, receiving the Doctorate from New York University in 1949.

## I. ABSTRACT

This paper is based upon an extensive study of the planning and scheduling of a CV33 class aircraft carrier at a Naval Shipyard. The research for this project extended over the past six years. This study contains data obtained and analyzed from the Navy Department, Naval Shipyards, private shipyards, a review of the literature on the subject, and is supplemented by the author's personal experience in this field.

An effort has been made to contribute to a better understanding of this complex subject. Effective planning and scheduling requires the clear visualization of the entire shipbuilding program. This is necessary to avoid bottlenecks, delays, confusion, excessive costs and construction time, and being swamped in a sea of apparently unrelated details and activities.

There are six major sections in this paper: historical background, planning, overall scheduling, master scheduling, detail scheduling, control, and discussion. Acknowledgments, suggestions for future study, conclusions, and a bibliography comprise the balance of this article.

In the discussion, operational analysis has been applied to determine the reduction in manpower and time on successive vessels. The manpower expenditures for various carriers have been analyzed to reveal their salient features. A recommended procedure for planning and scheduling is described, together with other suggestions for improvement. The philosophy underlying planning and scheduling rounds out the discussion.

* The material presented in this article was abstracted from the thesis submitted by the author in partial fulfillment of the requirements for the degree of Doctor of Engineering Science, College of Engineering, New York University.

## II. HISTORICAL BACKGROUND

The science of planning and scheduling as it is known in modern times, has developed during the past sixty years. As handicraft production was replaced with factory manufacturing, beginning about 1890, there arose a need for a new type of management and control. The work of four outstanding leaders, F. W. Taylor, H. L. Gantt, H. Emerson, and F. B. Gilbreth, is recognized in the field of industrial management.[1]

Extensive applications of the principles of planning and scheduling have been made by the shipbuilding industry. This has been necessary due to the great complexity of the work and the many trades involved. In 1900 Fawcett[2] stated that a wide variety of influences forced upon the shipbuilding industry the conviction that more expeditious work was necessary. At this time, emphasis was placed upon the mechanical features of ship construction, such as improvements in tools, machinery, and material handling.

It was not until the period of World War I that management began to appreciate the significance of proper organization and controls for the production of ships. Kennedy[3] was an early advocate of the application of industrial management principles in shipyard practice. In 1917 he wrote that the introduction of planning decreased the direct labor more than the slight increase in overhead for this function.

Churchill[4] made a study of twenty shipyards for the Emergency Fleet Corporation in 1918. He concluded that proper management was the solution to the shipbuilding problem. The major difficulties that Churchill found were:

1. Not using the best principles of management.
2. Not applying modern developments in management of successful industrial concerns to shipbuilding.
3. Not receiving materials as needed.
4. Not utilizing materials properly, with the correct trade balance by different occupations.

The efforts of the Industrial Management Section of the Emergency Fleet Corporation to apply industrial engineering to shipyard management were described by Howard.[5] He found that while certain changes of a mechanical nature could be made in some yards, they were of minor importance compared to the opportunities that existed in the methods of coordinating labor trades. Howard's estimate of the unnecessary waste and delay in ship construction placed 80% of the responsibility on poor organization and management and only 20% on the employees.

Ferguson[6] stated that the efficiency of shipbuilding labor could be increased by 20 to 50% through the use of proper production controls. The necessary essentials included master schedules, labor, stores and material control, and the detailed planning of labor operations.

Admiral Cochrane,[7] the wartime Chief of the Bureau of Ships, discussed naval shipbuilding during World War II. The construction of more than one hundred thousand ships and craft and their maintenance in good condition raised a multitude of problems. To control the entire program, it was necessary to make accurate estimates of amounts and delivery dates of materials and components required.

Bills of material were prepared for every type of vessel, stating the precise material requirements. The next step was to establish an erection schedule for each vessel type, showing the specific dates on which different material components were needed. This was based upon a general erection sequence, which indicated the order of ship construction. Without the system of controls used, Admiral Cochrane stated that it would

have been very difficult to push the shipbuilding program through the 1944 peak.

A quotation from an article on scheduling by Captain Hamilton[8] concludes this introductory discussion: "Whatever the fate of our magnificent effort for perpetual peace, there is always the possibility that the Government may be faced with a large production problem; that controls will have to be imposed to insure that the Nation's real emergency needs are taken care of before any labor effort or material are permitted to enter into less essential products. If that time comes, whether for war materials or other, and whether the war materials include Naval ships or some other currently unknown item of offense or defense, let it be hoped that the problem will be attacked with real managerial vision; that scheduling in its true sense will be required; and that the scheduling machinery is ordered by authoritative mandate and not grudingly accepted in an arbitrarily restricted minimum by high authority. If it is, the emergency itself will occupy the center of the stage instead of being forced to the wings by a secondarily caused production emergency, and the bills may all be paid off by an earlier generation."

## III. PLANNING

### *A. General*

The planning for a naval vessel involves the consideration of the various factors affecting the shipbuilding program, and the taking of effective action to produce the desired results. The major factors are organization, facilities, manpower, plans, and material. The planning and scheduling procedures to be discussed in this paper will be illustrated by applications to the CV33, *U.S.S. Kearsarge*.

This ship[9] was authorized by Act of Congress on 9 July 1942. The order for her building was placed with the New York Naval Shipyard on 7 August 1942; her keel was laid on 1 March 1944; launching took place in 5 May 1945; and commissioning occurred on 2 March 1946. Jane's "Fighting Ships"[10] describes this vessel as a modified CV9 class aircraft carrier of improved design, with a stronger flight deck and a more thorough internal subdivision. Her cost has been estimated at $90,000,000. The displacement is 27,100 tons, with 33,000 tons at full load.

### *B. Organization*

Once the contract for construction of the vessel has been awarded, the major planning actions commence. The first factor to consider is organization—of the shipyard in general and of the planning and scheduling group in particular. The Naval Shipyards are composed of line and staff departments and semi-line, semi-staff offices. Each of these is headed by an officer directly responsible to the Shipyard Commander for the satisfactory performance of the duties assigned.

If a capital vessel has not been constructed in the shipyard for some time, it may be necessary to add organizational units and increase the planning and scheduling group. Where a new construction program is already under way, the effect of the new vessel must be evaluated. The planning and scheduling procedures to be followed must be clearly formulated early in the program.

### *C. Facilities*

The construction of a naval vessel is one of the most intricate of engineering operations. The facilities required in a shipyard to accomplish this are extensive. The Design Data Handbook[11] of the Bureau of Yards and Docks has included the following factors for the location of a shipyard:

1. A situation upon a good harbor

of sufficient size, depth, and accessibility for vessels of the largest size and heaviest drafts.

2. A favorable location with respect to the principal lines of defense and interior communication.
3. Ground suitable for the construction of excavated docks and basins and for heavy structures.
4. Proximity to centers of labor and supplies of material.

Carmichael[12] has listed the facilities needed for a shipyard. They are launching ways, fitting out piers, cranes, shops, buildings, railway tracks, storehouses, power plant, mold loft, and machine tools. Proper planning for the construction of ships must insure that the necessary facilities are available in the right amount and efficiently laid out.

The shipbuilding industry expanded tremendously during World War II. At the end of hostilities it was estimated[13] that the Government had invested $2,306,000,000 in facilities for constructing and repairing ships. This wartime investment was about four times the total value of Government and private holdings prior to the war.

### *D. Manpower*

The keys to a successful shipbuilding program are control of facilities, manpower, plans, and material. The integration of these factors by the shipyard organization in a definite time interval, the construction period, produces the ship. The manpower considerations in ship construction, especially for naval work, are complex. There are a large number of trades performing much work of a highly specialized nature.

Civilian employees of the Navy Department[14] are subdivided into two main categories, the laborer, helper, and mechanical service and the classified service. The latter group includes professional, administrative, subprofessional, fiscal, and clerical employees. The tradesmen groups are laborers, apprentices and helpers, mechanics, and supervisors. Guide line descriptions of the various mechanical trades[15] have been prepared by the Navy Department.

The peak employment in the shipbuilding industry[16, 17] was in 1943. A total of 1,670,000 persons were engaged in the construction and repair of naval and merchant vessels. Of these, 324,000 were employed in Naval Shipyards. A study of the distribution of workers in 71% of all private shipyards in the country was made by the Bureau of Labor Statistics[18] in 1943. The percentage distribution was: supervisory workers—7.2; skilled workers—57.0; semiskilled workers—30.7; and unskilled workers—5.1.

Shipyards were faced with major problems during World War II. The Office of the Assistant Secretary of the Navy[19] listed the major manpower problems and difficulties at that time. They were: shortage of skilled employees and experienced supervisors; training and replacement of labor; necessity to retain many below-average workers; inexperience on the part of management, supervision and workers; and the inability to plan in advance for battle damage repairs.

In an effort to solve these problems, the Navy Department[19] conducted many surveys and studies. Some of the major actions taken to ease the situation were: establishment of an administrative and a management engineer's office; freezing of manpower ceilings for classified employees; addition of industrial relations specialists on the staff of the Assistant Secretary of the Navy; training, safety, and health programs; multiple shift operations; and exit interviews to reduce turnover.

### *E. Plans*

Before any ship construction can begin, it is necessary to develop working plans. They must be in sufficient detail

to permit the ordering, fabrication, and erection of material. The principles of warship design have been described by Commanders Manning and Schumacher.[20] The vessel's seagoing qualities, speed, radius of action, offensive power, and protection are determined by the Navy Department's General Board. General specifications for building ships are issued by the Bureau of Ships to indicate standard practice, quality of workmanship, and tests desired. For each new design, a volume is prepared, called the "Detail Specifications." It defines in detail the structure, machinery, and equipment, to permit a shipbuilder to prepare an estimate of cost, and if awarded the contract, to begin work.

Dickie[21] in 1902 discussed some of the reasons for the long time required to build a naval vessel. His paper centered about the design of ships. Dickie recommended that locations and dimensions of compartments, armor, armament, magazines, and arrangements of machinery, drainage, and ventilation not be subject to change after keel laying.

Any design changes after the beginning of construction are very costly and time-consuming. Dickie's suggestions have considerable merit, but they cannot be rigidly adhered to in the design of capital vessels. Especially during wartime, developments proceed rapidly. If certain design changes were not made, the ship might be outmoded before its completion. However, all design alterations ought to be screened very carefully. Only the very essential ones need be adopted during the construction period.

The position of the Navy Department[19] on this subject was stated in 1944 as follows: "Thus the vicissitudes of war demand the changing of related programs to fit the changing conditions. . . . The consequent necessity for many design changes based on battle experience seriously interfered with efficient work scheduling and production planning which unquestionably creates a certain amount of waste of manpower. But the Navy must be quick to keep abreast of all changes and be able to meet the demands of the Fleet in order to win victory as quickly as possible and with the fewest losses in men and equipment."

### *F. Material*

In the 27,100 tons comprising the CV33, there is to be found almost every type of material. Over 300 contractors from more than 24 states provided the 25,000 items required for the construction of this ship.[22] Steel is the principal item, for the structure, machinery, and armor. Copper, aluminum, lead, zinc, lumber, cork, rubber, and paint are other basic materials.

During the period of World War II, the Bureau of Ships controlled material procurement for the naval construction program. This was accomplished through the use of Component Percentage Schedules[23] and Guide Lists of BuShips Components.[24] Material for the CV33 was subdivided into 285 components including piping, machinery, electrical, equipment, ventilation, and outfit. The classification of the components was contained in the guide list. Admiral Cochrane[7] estimated in 1944 that for each worker in a shipyard two others were engaged in the production of materials and components for the shipbuilding program.

### *G. Bills of Material*

Bills of material, or B/Ms as they are generally called, are used to convey information for material procurement, fabrication, and erection. They itemize all materials required, with identifying plan numbers, quantities, and quality specifications. The source of supply for each item as indicated, such as outside procurement, stores, or local manufacture. A B/M shows the routing of the work by operations, as the material passes from one shop to another, until the entire unit is completed. Job order

numbers, cost and weight groups are also listed, to permit compiling of records of the vessel's cost and weight.

B/Ms are provided for structure, piping and tubing, electrical work, manufacturing requests, fittings, valves, allowance items, and miscellaneous equipment and material. During the war, the Controlled Materials Plan[25] required a statement of the amounts of controlled materials, steel, copper, and aluminum, needed for physical incorporation in the production of a given product, by means of B/Ms. A prototype B/M[7] was used for determining the allocation of controlled materials to the aircraft carrier program. It stated precisely how much of each material went into the hull at the building yard or into components or subcomponents at the factories.

## IV. OVERALL SCHEDULING

### *A. General*

When a contract is awarded to construct an aircraft carrier, the information generally available consists of a set of contract plans, general and detail specifications. From these must be developed a sound basis for the preparation of the necessary schedules. These schedules establish the guide lines to which all concerned with the construction of the vessel do their work. A good system of schedules, properly planned, makes for logical, orderly, economical, rapid, and efficient construction.

Scheduling a ship is best accomplished in three phases, overall, master, and detail. The overall scheduling phase consists of setting the cardinal dates, establishing a control calendar, determining the logical erection groups, and preparing the overall structural, outfitting, and completion schedule. During the interval between the award of the contract and keel laying, called the pre-keel period. this phase of scheduling ought to be accomplished.

### *B. Cardinal Dates*

The physical construction of a vessel covers the span between keel laying and final delivery. There is also a preliminary time called the pre-keel period following the contract award. During this interval arrangements must be made to commence the design and material procurement and to obtain the necessary organization, manpower, and facilities. The pre-keel period for the CV33 was six months. The sum of the pre-keel and construction periods is called the quasi-building period.

An aircraft carrier grows during construction in a manner which is difficult to follow. However, as in any growth process, there are certain well defined points which can be used as criteria for the various phases of construction. By scheduling work to be completed at these points, or cardinal dates, it is possible to set up a series of targets at which to direct all work schedules.

The cardinal dates are set in the original tender of bid for the vessel and form the basis for the subsequent scheduling. All departments concerned with the construction program at the shipyard must be consulted in setting these dates. In effect, they form a commitment of work in each department. The cardinal dates are contract award, keel laying, launching, commissioning, completion of construction, and completion of outfitting.

At keel laying, the earliest structural assemblies must be available for erection. The date of launching requires that a good portion of the structure be completed, with the watertight subdivisions proven by tests, and that the outfitting be well under way. Commissioning is one of the high points in the vessel's history. On this date the vessel is turned over to the custody of the Navy, and

her officers and crew move aboard. Outfitting must be practically completed to make the ship habitable.

In the completion of construction and completion of outfitting periods, usually of several weeks' duration, all that remains is to correct any defects found, add the special items of outfit, and perform the work required by the Trial Board. For a Naval Shipyard, the completion of construction date is equivalent to that when the vessel leaves the private yard for the final outfit installation at a Naval Shipyard. Finally, the official delivery of the vessel is made to the Fleet. Henceforth, any work on the vessel is considered as a repair or an alteration, except for incomplete work items or correction of defects of the building yard's responsibility. A specified guarantee period, usually about one year, is provided in the contract for each vessel.

### *C. Control Calendar*

Experience in building ships during wartime indicated that the requirements of the naval program were subject to wide changes as strategic and tactical situations developed. Basic considerations such as design alterations, material delays, manpower shortages also contributed to produce a situation where shifts in the cardinal dates of the vessel were frequently necessary.

Were it the practice to issue the various schedules with actual dates specified, each major change in the building program would necessitate reissue of many schedules. To obviate the need for this, schedules are best issued to specify erection week numbers rather than actual dates.

The control calendar provides the means for relating calendar dates to erection week numbers. The modification of schedules to correct for changes in the building program is accomplished by altering the calendar dates corresponding to the erection weeks on the control calendar.

### *D. Logical Erection Groups*

The contract plans developed by the Preliminary Design Section of the Bureau of Ships include the inboard and outboard profile and the compartment and access plans. These show the principal structural subdivisions, such as wing tanks, longitudinal and transverse bulkheads, and decks.

With this information on hand, the entire structure of the carrier is broken down into the logical erection groups for ship construction. These groups form the basis for sub-assemblies, prefabricated before shipboard erection. Every structural element falls into one of these erection groups. Each erection group is bounded by transverse and longitudinal bulkheads, and includes the overhead deck plating. Foundations are considered to be integral with the deck plating, and hence are part of the erection group of the deck beneath. There were fifteen erection groups for the CV33 class.

### *E. Overall Structural, Outfitting and Completion Schedule*

A most valuable schedule is the overall structural, outfitting, and completion schedule. Its purpose is to outline the proposed sequence for constructing the vessel. It embraces the plan and material requirements, shop fabrication, structural erection, outfitting (including piping, machinery, electrical, ventilation and other work), testing, check-off of installations, and completion of the ship.

The overall schedule must be prepared immediately after receipt of the contract to construct the ship, following the setting of the cardinal dates. The considerations that enter into its preparation are the manpower availability, type of design, material situation, and general program for the shipyard. All departments involved must be consulted to obtain an accurate picture of their individual needs.

The information can be presented either graphically or in tabular form. In either case, the schedule sets the relationship among the type of work, its physical location aboard ship, and time. The physical locations used for a carrier are areas between main transverse bulkheads, by levels. The levels are innerbottom, wing tanks, machinery spaces, hold, second platform, first platform, fourth, third, second, main, forecastle, gallery, and flight decks, and island. Time is expressed in terms of erection week numbers, converted from calendar dates by the control calendar.

If a graph is used, the overall structural, outfitting, and completion schedule lists the physical location as the ordinate and time as the abscissa. The allowable time intervals to provide plans and material, shop fabrication, structural erection, outfitting, testing, and final completion for each area are plotted. In tabular form the same information is listed with the time intervals specified for each of these functions.

This schedule provides the primary guide, toward which all subsequent planning and scheduling is directed. Once the general plan, which this schedule represents, is approved, each activity has a basis on which to prepare its own schedules. At all times, it is essential to coordinate the plan, material, manpower, shop, and ship work schedules to insure the proper sequence of work, eliminate interferences, and maintain control over the construction of the vessel.

The limiting dates on this schedule provide the ultimate criteria for checking the various schedules that are later prepared in greater detail. With the entire picture of the job at hand, scheduling is greatly simplified. The unsatisfactory practice of picking dates "out of the air" for specific work in compartments, without guide lines, is eliminated by use of this method of scheduling.

## V. MASTER SCHEDULING

### *A. General*

Master scheduling is the second phase in scheduling a carrier under construction. It embraces plans, material, shop fabrication, structure, piping, machinery, electrical, ventilation, outfitting, testing, and painting. This phase is commenced in the pre-keel period, and it ought to be completed prior to launching the vessel. A discussion of each of the elements of master scheduling follows.

### *B. Plans*

Plan schedules are prepared for the hull, machinery, and electrical work of the vessel. In addition, special schedules are made, as required, for aeronautical, electronics, and ordnance work. At all times, the proper sequence of shipboard work must be considered in developing plan schedules. The overall schedule previously discussed provides a guide line for plan scheduling. In addition, the other master schedules to be described list the dates when plans are required.

Solov[26] described the scheduling of the work of the Design Branch at the New York Naval Shipyard during the recent war. The date to start plan design is determined by the following factors, listed in inverse order of occurrence: date of shipboard erection, fabrication interval of material, material procurement lead time, and design period.

A plan list is prepared for each vessel, with the exact titles of the plans. As the work progresses, the list may be modified, but these changes are relatively few. Detail plans must be issued prior to the start of shop fabrication.

Arrangement plans are necessary to determine material requirements. Certain plans must be developed before work can start on others. This is due to the close interrelationship of the various systems aboard ship, which are often in close proximity.

Ferguson and Blewett[27] described a method of analysis of design work by means of a group plan dependence diagram. A tentative plan list is drawn up and studied jointly by the design and operating departments. The chart supplies the data for the groups affected by each plan. From this, the earliest date when each plan is needed is set. Final issue dates are determined for each plan and no changes are allowed without the approval of the department concerned. The dependent sequence diagram[28] illustrates graphically the hold-ups that can occur on succeeding work due to a plan issue delay.

### *C. Material*

The material requirements for a ship must be carefully considered in the preparation of material schedules. There is a definite relationship between the growth of a ship and its material needs. The factors affecting material scheduling include the shop fabrication interval, the type of component, its size and relative location on board ship, and the testing period.

Material demands for the shipbuilding program were so tremendous during the war years that it was necessary to control material scheduling at the Navy Department level. The objectives of this scheduling by the Bureau of Ships[29] were:

1. Correct placement of orders, identified by end use and scheduled to establish relative urgency.
2. Early placement of orders to avoid the disruptive effects of emergency production.
3. Development of realistic production schedules in the plants of manufacturers.
4. Use of available surpluses wherever possible to save critical materials, production capacity, and manpower.

In order to set realistic material schedules, the Bureau of Ships consulted with the various Naval Shipyards and private shipbuilders. The estimated material requirements for several vessels of the same prototype design were matched to the quasi-building period. By averaging and weighting the times when each component was required, expressed as percentages of the quasi-building period, a material schedule was prepared. It represented the best opinion of the material needs for each type of ship.

This schedule, known as the Component Percentage Schedule[23] was issued by the Bureau of Ships to control the entire material procurement program for naval vessels. This schedule listed the percentage or days before end of construction when each component was required at the shipyard. A table of required shipment dates, assuming a fifteen-day shipping period, accompanied each material erection schedule. Where extensive shipyard fabrication was required, the manufacturer had to ship early enough to allow for this interval. Neuhaus[30] has described the scheduling of naval material by the Bureau of Ships during World War II.

### *D. Shop Fabrication*

Shop fabrication schedules are generally made in connection with the master structure, piping, machinery, and other schedules. To prepare shop fabrication schedules, it is necessary to have full information concerning the design of the vessel, material procurement program, shop backlog and anticipated workload, shop facilities, and manpower.

The scheduler must take these factors into consideration in preparing his estimates. A knowledge of the design of the vessel tells him what each system is composed of, its extent, and the rela-

tionship of each component to the whole. The material procurement program must be clearly established and understood by all parties. In some cases, raw material is purchased for shop fabrication. At other times, semi-finished items are obtained or the articles may be bought ready for installation.

During slack periods it is advantageous to fabricate as many articles as possible from raw materials to absorb the excess manpower and avoid layoffs or shifting of men. The availability of facilities and manpower in each shop are the final determinants on fabrication procedures, policies and schedules. At the height of the war, a Farming Out Board[31] was established in the New York Naval Shipyard to help the shops meet their peak loads by securing the services of outside contractors to fabricate material. Some of the items farmed out were hull structure, foundations, ventilation ducts, and castings.

The relationship of one shop's work to another's in the shop fabrication procedure determines certain sequences for scheduling. For example, an extensive built up section might include the pattern, foundry, and machine shops. Many systems require a coordination of effort for various shops. The firemain system is installed mainly by the pipefitters, while the shipfitters and welders install and secure foundations, the machinists place the pumps and hydraulic controls, and the electricians provide the necessary power and control wiring. Shop fabrication must be scheduled so that each item in a system is ready for installation aboard ship in its proper sequence.

### *E. Structure*

The structural erection schedule is the next master schedule prepared. The vessel has been broken down into logical erection groups. The various sub-assemblies have been agreed upon and policy set concerning which structure is to be fabricated at the yard and which is to be farmed out. The overall structural, outfitting, and completion schedule has set the limits for structural erection.

The general practice for structural erection of an aircraft carrier is to work from the centerline outboard, from the midships section forward and aft, and from the keel upwards. With this in mind, the structural areas are scheduled, setting overall dates for the start and completion of each section. It is desirable to erect the inner bottoms and wing tanks as rapidly as possible to establish the machinery space boundaries and decking. The most intricate and heavy work is located in the machinery spaces. Early availability of structure in this area allows for an early start on piping, machinery, and electrical installations.

The stern of the vessel requires considerably more effort to complete than the bow. This is due to the greater complexity of the stern, with its shaft alleys, stern tubes, struts, rudder weldments, and other complicated structural arrangements.

There is an optimum tonnage which can be erected weekly. This depends upon the crane capacity, type of structure, and size of the sub-assemblies. A tonnage erection rate is set, considering these factors, to provide a basis for scheduling the structure. The tonnage of the vessel can be estimated by erection groups from the detail specifications, contract plans, and past experience. Once the tonnage and the tonnage erection rate have been determined, the erection of each structural erection group can be scheduled. This must not be out of line with the overall schedule for the vessel, or the ship may be delayed.

A wide variety of related structural work is often included under the generic heading of structural schedules. In the strict sense, they are mainly outfitting items, but they form an integral part of the structure and are often included therein. Examples of these items are armor, bolted plate covers, foundations, hatches, manholes, and scuttles.

*F. Piping*

Piping work is one of the earliest installed aboard ship. It follows the structural erection as closely as practicable. The coppersmiths, pipefitters, plumbers, and laggers are required to perform their installations in virtually every part of the vessel, from the main drainage system in the inner bottoms to the fresh water system in the island. The overall structural, outfitting, and completion schedule, which sets the outfitting limits for each deck and area is used as the guide for master piping scheduling.

The main systems are scheduled to start shipboard installation immediately upon the structure becoming available. Much of the tank outfitting is difficult work, due to the poor access to these spaces. However, during shop subassembly of the structure, these areas are frequently available for pipe installation. If this is not feasible, then the work is best done immediately after the shipfitters and welders complete the structure, and while the access is clear.

The balancing of the manpower available with the workload is another important factor in setting piping and other schedules. To do this, it is necessary to list each piping system, broken down by decks and areas. A rough estimate of the manpower required for each area is made. By establishing an approximate schedule of the piping installations, the estimated manpower load for the ship can be calculated. The manpower loading is best when it is approximately trapezoidal in shape, with a moderate rate at the start, a level load for most of the construction period, and a tapering off at the end of construction. The manpower curve must then be added to the pipe shop's manpower curve for all productive work, including other new construction, the known and estimated repair work, and manufacturing. The schedule must be adjusted if the available manpower is less than the scheduled work load. Excessive peaks or temporary declines in manpower curves are to be avoided. On occasion, it is necessary to modify the piping schedule somewhat in order to preserve an overall manpower curve of reasonable proportions for the pipe shop. When this must be done, the least important piping systems provide the cushion, and can more easily be shifted from one scheduled date to another within allowable limits.

The piping work for a carrier may be placed in three categories: critical, which must be installed at a specific period; important, which should be installed at a specific period, but can be scheduled with greater leeway; and other work, which can be installed at any time within the availability of the area for outfitting work.

Critical piping includes all piping within tanks, much piping within machinery spaces, most piping to equipment, and certain of the main piping systems. It is essential to install piping within tanks early due to the penetrations that are made in the bulkheads, the general difficulty of access, and the need to complete the tanks, test them, and lock them up before launching the ship. Machinery spaces contain a great deal of piping, and the work must be started early with close control over the main systems to allow the early start of the machinery tests. Another type of critical work is that for hydraulic units, such as the inboard elevators. The major systems running through the ship must get an early start because of their magnitude. Delays in the firemain, fresh water, gasoline, and steam lines seriously interfere with other work. If the main runs are not carefully controlled, other ship work including ventilation and equipment installation, testing, and painting may be delayed.

Important piping includes the balance of work within the machinery spaces, hydraulically operated valves, refrigeration piping, and sprinkling systems.

Other piping work includes the balance of the systems which can be installed at any period within the limits set by the overall schedule for completion of each area. It is this type of work, including plumbing, fixtures, drains, vents, and scuppers which furnishes the reservoir for absorbing additional manpower or for providing help on work of higher priority which falls behind schedule.

For proper control of work, the plans, material, facilities and manpower must be available as required. Therefore, the plan and material schedules, previously discussed, need to be coordinated to provide full plan information and materials as they will be needed.

*G. Machinery*

Machinery master schedules are prepared for all the work under the cognizance of the machinery ship superintendent. This work formerly was handled by the Bureau of Engineering, prior to its consolidation with the Bureau of Construction and Repair to form the Bureau of Ships. It is important to note that "machinery" is here used in this restrictive sense, since the hull ship superintendent is responsible for a great deal of machinery, scheduled under the heading of "outfitting."

The work controlled by the machinery master schedule comprises installations in fire, engine, and auxiliary machinery rooms, and miscellaneous other compartments. The scheduling of main machinery is governed by the cardinal dates, overall schedule, material receipt of main boilers, turbines, reduction gears, condensers, and similar equipment, foundations, closing of overhead decks, and tests.

It is desirable to locate and install the main units on a carrier before the overhead structure is erected. There is less effort required to ship the equipment and it avoids the necessity of leaving large openings in the structure for the later installation of machinery. Once the main units have been installed, other work, such as piping, ventilation, wiring, and operating controls can proceed more effectively. Elaborate shipping openings and other provisions must be made if machinery is not installed before the overhead decks are layed down. There have been cases where the fourth, third, second, and main decks could not be completed for this reason. This delayed all work in those areas.

*H. Electrical*

In recent years there has been a widespread increase in the amount, type, and complexity of electrical work aboard naval vessels. This type of work, in general, extends throughout the vessel and requires a large amount of time to install and test due to its intricacy. The electrical master schedules include the following divisions of work for an aircraft carrier: cable racks, degaussing, fire control, interior communication, lighting, panels and switchboards, power, radio and radar, and special installations.

Unlike piping systems which can be broken and connected, electrical lines must be pulled for their entire length from the source of current to the switchboards, panels, or other connecting units. Accordingly, an early start on board ship is necessary for the installation of the main runs of cable and their test. Where electrical work is not started early and carefully controlled, it can easily get out of hand and result in a delay to the completion of the ship, or in the need for an excessively large force of electricians aboard ship at the end of the construction period to complete the work.

*I. Ventilation*

Ventilation systems include both natural and mechanical supply and exhaust. The equipment used with the duct work on these systems includes blowers, cooling coils, fans, heaters, lagging, operating controls and gear, sliding covers, and valves. The scheduling of ventilating systems must take into account the relatively bulky size of most duct work.

By careful designing, most interferences can be prevented. However, it is necessary to prepare templates for fabricating much of the sheetmetal. Measurements are taken aboard ship, and any interferences that are found are corrected.

Generally, ventilation work follows the heavy installations of the pipe and electric shops, such as the firemain and main cable runs. Duct work is lighter and therefore can be moved more readily than pipes and cables, although its size is larger.

The penetration through watertight compartments, armor decks, and similar structure must be scheduled prior to the time those compartments are tested for tightness. This necessitates close control over the machinery spaces, magazines, and other installations in the lower levels of the vessel.

Foundations for fans, blowers, and control equipment must be scheduled for installation in time to allow for placing the machinery as needed. The vent systems cannot be completed until these items are installed. Usually, this equipment is placed during the first third or half of the installation period for the ventilation. Various tests are required of ventilation systems. Tightness, operation, and control features are checked. Systems must be completed in all respects to be ready for the operational tests.

### *J. Outfitting*

An aircraft carrier is a vast, complex, self-sufficient naval vessel. The work involved in outfitting a carrier is tremendous. It can be broken down into the following categories, among others: berthing, equipment, fittings, furniture, instruments, insulation, label plates, stowages, and other items of outfit.

The scheduling of outfitting work is systematized by breaking the work down into its components as indicated, and setting dates for each type of work. The overall schedule provides general guidance for setting limiting dates in each area of the ship. Installation periods for each type of outfitting material is thus narrowed down within defined limits.

For heavy items, such as elevator power plants, commissary and galley equipment, steering gear, and windlass, it is best to schedule the installation to follow shortly after the structural availability. This reduces the number of deck openings that are needed for shipping machinery. In addition, it allows ample time for the extensive piping, wiring, and other work required for this type of installation.

Many of the outfitting systems can be scheduled to balance the manpower requirements for each trade. These jobs provide a reservoir of work which can be adjusted to eliminate manpower peaks or to absorb available manpower, as long as the overall dates for completion of all outfitting are met.

### *K. Testing*

Testing schedules are prepared as the final link between ship construction and completion. An efficient test section, working in accordance with a well prepared test schedule, can serve to expedite the final completion of work. Since difficulties, improper installations, and defective equipment may be encountered on tests, it is imperative to allow a safety margin in scheduling tests in relation to the ship's completion. An early start on testing is a valuable aid in setting the construction pace to be followed during the building period.

Inspections and tests for new construction cover all portions of the vessel. Structure, piping, machinery, electrical, ventilation, and outfitting work are all tested and inspected. This is to demonstrate satisfactory workmanship, adequate strength, rigidity, tightness, suitability for the purpose intended, provision and maintenance of proper clearances, and to determine that all requirements have been satisfactorily fulfilled.

The general and detail specifications provide the requirements to be met. The Design Branch issues test memoranda, enumerating the procedures to be followed. The various master schedules issued set the test periods for each type of work.

### *L. Painting*

The painting work for a ship under construction is described in the general and detail specifications for the vessel. The Design Branch issues painting instructions which outline the type of painting required for each section of the vessel. The work can be subdivided into interior and exterior categories. Painting is usually done in two stages. The first part, involving the primer coat of paint is applied to prevent corrosion to the steel shortly after its receipt. Touch-up work as necessary is done after shipboard erection.

For interior work, the second coat is applied after outfitting has been completed in the compartments. The exception is fuel oil tanks where the primer coat is removed after erection of the structure to prevent the oil from dissolving the paint. It is desirable for the painters to be the last trade to enter the compartments. Upon completion of their work, the compartments should be inspected and locked up, to give the spaces ample time to dry without being soiled by further work from any other trade. Then, at commissioning, the ship is turned over to the Navy in a clean condition. When compartments are left open, experience has shown that the paint is scratched, marred, and soiled by persons passing through the spaces. Additional painting is necessitated, increasing the time and cost of the work.

For exterior work, the launching date determines the completion of most of the hull painting. Since this marks the period when the ship becomes water borne, the final painting must be applied to prevent corrosion, fouling of the ship's bottom, and other effects of the water. Some special painting work is required on the exterior, such as boot topping, applied between certain water lines, to provide a water, air, and grease resistant surface.

## VI. DETAIL SCHEDULING

### *A. General*

The two preceding chapters have been devoted to a discussion of overall and master scheduling. In many cases, work can be satisfactorily and economically controlled through their use. There are certain types of work, however, where a finer degree of control is indicated. Careful judgment must be exercised in the selection of the kind of scheduling to use. It costs money and consumes time to prepare schedules, distribute them to all activities, and carry them out. A large amount of paperwork of itself is no assurance of good scheduling.

When an orderly sequence of work has been established, when plans, material, facilities, and manpower have been coordinated, and when limiting dates have been set for all work, then the objectives of scheduling have been met. A discussion of detail scheduling for an aircraft carrier follows. This type of scheduling generally runs from the prekeel period for the preliminary compartment completion schedule to the final delivery of the vessel for the special spot schedules and weekly summary lists.

### *B. Preliminary Compartment Completion*

The first detail schedule prepared is the preliminary compartment completion schedule. It is based upon the overall schedule and is issued by levels. Each compartment and space on the vessel is listed by number, description, and location. The compartments are grouped together by the areas specified on the overall schedule. This compartment

schedule specifies the erection weeks for structure to be completed sufficiently to allow the outfitting trades to begin work; for the strength and tightness test; for the final tightness test, after all bulkhead and deck penetrations have been made; and for final completion of all work, including testing, check-off of equipment and painting.

It is important to note that this schedule is an idealized one, based upon the building pattern selected for the ship. In general, work starts at the lowest level, amidships, and progresses forward and aft, outboard from the centerline, and upwards. Certain highly specialized compartments may require an extension of their completion dates beyond the normal period for the area. This may be due to the heavy workload, limited working space, delays due to late delivery of equipment, or dependence upon other areas for final testing of systems, especially in the case of electrical installations.

However, these considerations need not prevent the establishment of an orderly rate of structural completion, compartment testing, outfitting, system testing, and painting. A steady pace of work promotes efficient and rapid construction. Allowances can be made for specific compartments, such as fire and engine rooms, pump rooms, and the combat information center. The best practice is to set up the idealized compartment completion schedule and follow it as closely as possible. Each exception permitted is a potential cause of delay in the delivery of the vessel. As much work as possible should be completed within the normal limits of this schedule in those exceptional compartments mentioned above.

The preliminary compartment completion schedule can be analyzed graphically. With the areas from the bow to the stern as the ordinate and time as the abscissa, the number of compartments on each level by areas scheduled each week for structural completion, strength and tightness test, final tightness test, and final completion can be plotted. It is best to use a different color for each level and a different symbol for each operation. The number of compartments involved can be written within each of these symbols. This demonstrates graphically the pattern to be followed in constructing the ship. A recapitulation of this information at the bottom of the sheet shows the pace established. This form of presentation has proven useful in explaining the preliminary compartment completion schedule to top management and to the various trades involved. The purpose and reasoning behind the dates set on the schedule can be visualized this way, and it materially assists in securing acceptance for the detail schedule.

### *C. Plan Cross Index*

As the development and issue of plans proceeds, a plan cross index is prepared. Compartments are plotted by compartment numbers, within each structural erection group or area against plan numbers and titles involved in the compartments. A mark is placed in the appropriate space to indicate that the plan applies to the particular compartment. The main value of this index is for quickly and conveniently determining the types of work involved in each space aboard the ship.

### *D. Structure*

The structure of the CV33 class was subdivided into fifteen erection groups for purposes of subassembly and erection. The master schedules for the structure set the overall dates for this work. A finer control is possible through the use of a hull structure schedule. A list of the principal structural plans within each erection group, excluding detail and standard plans, is prepared. Based upon the master structural schedule, the shipboard erection, shop fabrication, and plan and material due dates are set. Any work that is farmed out is also listed on

this structural schedule as well as the dates for the assist shops, including welders, shipwrights, and painters. This type of schedule can be adapted to provide for shop installation of piping work within the tank subassemblies.

The dates specified for structural completion on this schedule must agree as closely as possible with those set on the preliminary compartment completion schedule. The shipfitter shop is the lead shop on all new construction work. Therefore, it is essential that this schedule be closely followed. All other ship erection work follows the structure. Any structural delays are passed down the line to all succeeding trades and can create serious difficulties at a later time. The planning and scheduling of the piping, machinery, electrical, outfitting, and other work must be done almost simultaneously with that for the structure. Thus, schedules for other work must be based upon the structure being available as indicated.

### *E. Areas*

The vessel has been broken down into areas, extending between main transverse bulkheads by levels on the overall structural, outfitting, and completion schedule. The various master schedules have set the plan issue, material receipt, shop fabrication, installation, and test dates. A finer degree of control for structure has been outlined, and in a similar manner, other ship work can be handled in detail by area scheduling.

Area scheduling is done in two steps. First each master schedule is subdivided into areas by decks. The limiting dates specified on the preliminary compartment completion schedule, for ship outfitting must be observed, as far as possible. The detailed schedules thus developed from the master schedules are not suitable for issue to the field because they lack full coordination. Hence, the second step in detail scheduling by areas is to coordinate all work. An orderly sequence of operations must be established, setting the priority of the trades. When this is carefully accomplished, trade interferences and unnecessary delays can be largely eliminated.

The form in which to issue the area schedule is a matter of sound judgment. It is bad practice to issue too many pieces of paper because the field finds difficulty in keeping track of them. In addition, if scheduling is attempted in too great detail, it may fall down of its own weight, due to the volume of work involved and the effect of minor plan alterations, material delays, and similar factors. Some compromise is necessary, and only actual experience can supply the best answer. Where plans and material are available, where there is sufficient manpower, and where economy is stressed in preference to speed of construction, scheduling in great detail is indicated. The experience of the New Construction Planning and Scheduling Group at the New York Naval Shipyard during the scheduling of the CV33 demonstrated that under wartime conditions, stressing speed, with material shortages, manpower diverted to repair work of greater priority, and frequent design changes, the best that could be obtained was accomplished by master scheduling.

### *F. Final Compartment Completion*

The final compartment completion schedule is prepared after the plans have been issued for the ship. A separate schedule is made for each compartment or space aboard the carrier. Its purpose is to provide a complete summary of work by equipment, system, and machinery within each compartment. In general, this schedule is issued by levels, starting with the inner bottoms. It is based upon the preliminary compartment completion schedule for limiting dates, upon the plan cross index for the applicable plans, and upon the area schedules for the sequence of work. While it was not used for scheduling purposes on the CV33, this form did

prove of value as a check list of work to be accomplished in each compartment.

Where scheduling is feasible in great detail, the final compartment completion schedule in conjunction with the area schedules provides the means for accomplishing this. The problem of trade interferences can be eliminated or greatly reduced, provided this schedule is carefully prepared and as carefully carried out. The main value for this type of schedule is in areas of high complexity and limited working space where the trade sequence must be controlled in great detail. Fire and engine rooms, pump rooms, and the combat information center are examples.

### *G. Weekly Summary Lists*

From the schedules discussed in the previous sections, weekly summary lists of schedules plan issues, material deliveries, and shop and ship events for each erection week can be prepared and issued. They should be sent to all activities about two weeks in advance of the erection week specified. This list serves the twofold purpose of setting up a priority system for urgent work and providing a check list of work to be completed. The weekly summary list can be used to provide a record of progress of work by requiring a signed copy to be returned to the scheduling section with the status indicated.

### *H. Special Spot Schedules*

There are certain jobs for a carrier which may require special scheduling. These include the deck edge and inboard elevators, main shafting, the gasoline operating test, and launching. The schedules previously described may not provide the degree of control desired for this type of work, extending for a considerable distance through many sections of the vessel. In these cases, special spot schedules may be prepared, right on the job if necessary, to accomplish this purpose. Where bottlenecks and serious delays develop, special schedules sometimes serve as an expedient to prevent further difficulties and to set the priority of work to be done.

Toward the end of construction, it is advisable to survey the entire progress of the ship and reschedule those jobs which may be lagging seriously. As a general rule, it is wise to keep these exceptions to an absolute minimum and concentrate effort upon meeting the scheduled date of each job as it comes due. This will go a long way toward assuring economical and timely completion of the ship.

### *I. Electrical Schematics*

To assist in the installation and test of complex electrical circuits, schematic drawings can be prepared. These are in diagrammatic form and show the various components to be connected and tested. A single line drawing is issued, using standard symbols for cables, connection boxes, switches, controllers, and other items. Since most electrical plans are issued as deck or isometric drawings, the electrical schematics are of assistance in following a particular circuit. Schematics can be marked up to show the progress of the electrical installations and tests.

## VII. CONTROL

### *A. General*

An orderly sequence of work is established by planning and scheduling. Where the proper control measures are included, the methods used by men, operating machines, to fashion material into the final product, a ship, accomplish this purpose with a minimum of money and a maximum of efficiency and speed. Organization for executive control of ship production was discussed by Ayre[32]. He stated: "In the shipbuilding industry where the proportion of

labor cost is relatively high, there must in consequence be a large field for scientific thought, analysis, and research, with a view also to cost reduction. This, combined with the very fact of the complexity with which any organization for production is confronted, only makes this subject all the more important."

*B. Production*

The purpose of production control is to facilitate and insure the timely and economical completion of work in accordance with the specifications. The principal elements involved in production control at a Naval Shipyard have been classified by Captain Whitaker[33] as:

1. Timely determination of work desired
2. Detailed investigation upon which to base planning action
3. Timely issuance of design information
4. Timely issuance of complete specifications and estimates
5. Timely procurement of material
6. Maintenance of a balanced working force, properly distributed by trades and skills
7. Maintenance of tools, plant equipment and shop stores
8. Detailed coordination and scheduling of work
9. Planning and manning work for scheduled accomplishment at individual shop and trade levels
10. Progressing of work, including availability of information, material, equipment, and personnel, as well as collection of data relating to physical progress and comparison with scheduled progress
11. Inspecting and testing of work

Material control in the shipbuilding industry was outlined by Rinaldo and Fitton[34]. They stated that material control is the foundation of low costs and efficiency in the industry. Much time was lost by shipyard employees due to delayed, defective and wrong material. The success of scheduling depends upon accurate material control. Where a good system of material control is instituted, Rinaldo and Fitton stated that savings in labor and time of 15% or more could be found.

*C. Cost*

The term cost control, in its most general sense, may be defined as the guidance and regulation of the internal operations of a concern, by means of modern methods of cost accounting. Cost control is not static and is not history recording. Rather, its entire emphasis is on the taking of definite actions to improve, correct, or maintain the desired results. This is accomplished through the preplanning of expected performance and through the comparison of the actual results with these plans.

The cost of a ship includes direct material, direct labor and overhead. Ship cost and labor estimating has been described by Neuhaus[35, 36]. Sound estimates are needed for administrative information, budget planning, cost control, bid submission, and contract negotiation. Detailed cost estimating is required to obtain reliable results. In turn this necessitates a good cost accounting system at the shipyard, sufficient design detail upon which to base judgment, and cost trends over a period of years.

Vice Admiral Cochrane[37] stated that the construction of large naval vessels during World War II was greatly affected by a number of circumstances. These included the extreme urgency of much of this work, necessitating the use of large numbers of unskilled and untrained people, the introduction into the building program of yards with little prior experience with large vessels; the use of shift and overtime work; and the continuous interruption in the smooth flow of work in the Naval Shipyards due to the necessity

for shifting men even from highest priority construction to voyage repairs and battle damage repairs of existing ships. Admiral Cochrane estimated that the second vessel of an order of four would cost 15% less than the initial vessel, the third perhaps 18% less, and the fourth of an order of 21% less.

*D. Progress*

In order to determine whether a ship under construction is proceeding satisfactorily, it is essential to know with accuracy the progress of work at all times. The Bureau of Ships[38] has issued standard instructions for preparing and submitting progress reports. Within ten days of the award of the contract the Bureau required the estimated keel laying, launching, and end of construction dates, together with a statement of the effect of the new contract on schedules of any vessels previously awarded.

A monthly progress report was also required by the Bureau of Ships for all district craft and larger vessels. It was made out as of the first of each month and covered the progress made during the previous month, the total progress to date, predicted and/or actual dates of principal events in the construction of the vessels, and other pertinent construction data. In order that the progress date reported would be comparable for various shipyards, the Bureau adopted a uniform method for calculating the percentage of completion.

The rate of progress and manpower expenditures during the building period for three CV33 class aircraft carriers, vessels C, D, and E, and three other capital vessels, F, G, and H, are shown on Figure 1. The Bureau of Ships' method of reporting progress was used. The allowance for material received (up to a maximum of 38% of the total progress) accounts for the greater rate of increase of progress than manpower expenditures during the early portion of the building period. Since the pre-keel periods were six months, the various curves start between 10% and 20% of the building period. It is interesting to note that most of these curves are of the normal growth type.

In Figures 2 and 3, the rate of progress and manpower expenditures for each shop of the CV33 class carrier, D, are plotted during the building period. Those shops expending 50% or more of their manpower in the first 50% of the building period were the shipfitter and inside machine shops. The sheetmetal, outside machinist, electric, paint, and miscellaneous shops expended 20% or less of their total manpower during the first 50% of this building period.

The various master schedules previously described and illustrated can be used for reporting the status of work under construction. By considering each of these schedules as a modified Gantt chart, the physical progress of work can be compared with the scheduled progress graphically. To do this, it is necessary to measure the actual work performed and plot it on the master schedules, adjacent to the scheduled lines on the sheets. In addition, the weekly summary lists can be used to report the progress of work, as previously described.

## VIII. DISCUSSION

*A. Recommended Procedure for Planning and Scheduling*

The various aspects of planning and scheduling a CV33 class aircraft carrier at a Naval Shipyard have been examined in this paper. There is a recommended procedure for planning and scheduling for efficient ship construction. All factors affecting the work, including organization, facilities, man-

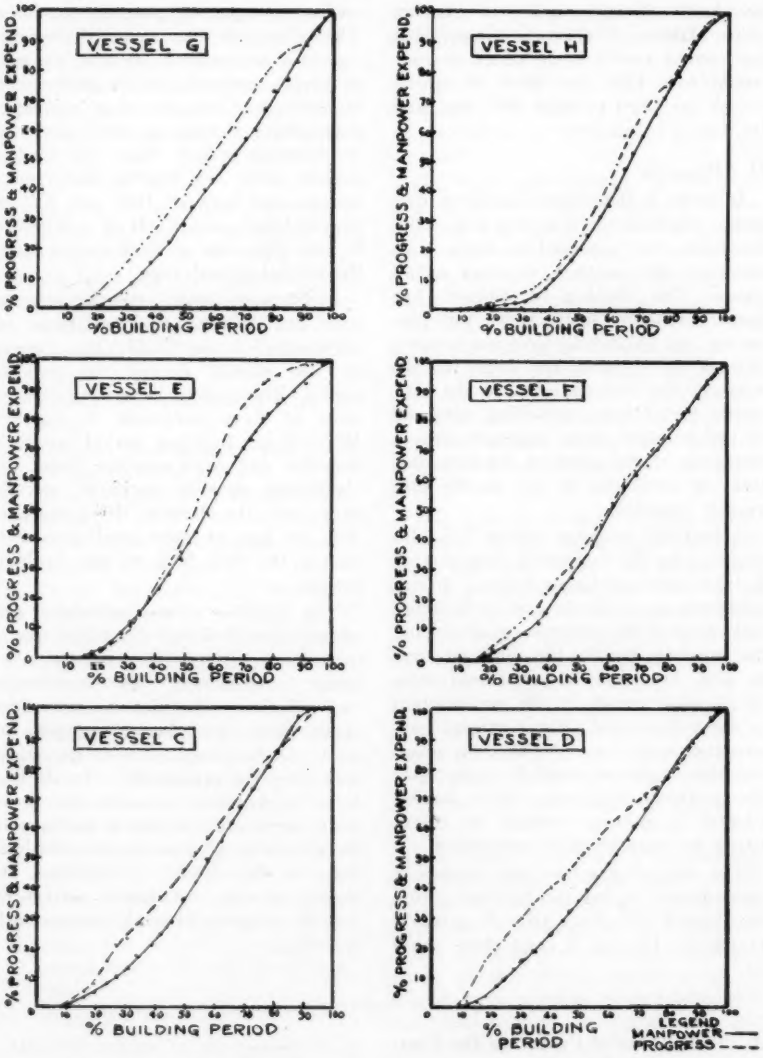


FIGURE 1.—Rate of progress & manpower expenditures during building period for CV33 class aircraft carriers & other capital vessels.

power, plans, and material, must be integrated into a definite pattern with regard to time. Failure to include any of these major factors, and their interrelationships, in the scheme of planning and scheduling is certain to lead to difficulties. The "sine qua non" of a successful program is good coordination of the many diverse elements in a Naval Shipyard.

It is considered necessary for the major planning, overall, and master scheduling to be performed at a high level in the organization. Every department, division, and office in a Naval Shipyard must contribute its share of the effort in the building of ships. The only way to insure that all activities are properly coordinated is to place the coordination groups in a position of authority commensurate with its responsibility. Where the organizational level is not sufficiently high, it is difficult for the schedulers to do much about plans, B/Ms, and material. Furthermore, when the total Yard workload is not taken into consideration and manpower allocated to each type of work, men may not be available to perform the scheduled tasks. This may result in the assumption that all factors outside of the span of control of the planning and scheduling section are ready and available as needed, whereas they may not be.

The Planning and Estimating Branch of the Planning Department of Naval Shipyards occupies the central planning position. It authorizes all work, initiates design action, issues B/Ms, prepares material procurement requests, and is in the best position for knowing the present and contemplated work load. P. & E. estimates all work and prepares the job orders and specifications for each job. By virtue of its organizational level, P. & E. is thus best situated for controlling design action, material procurement, work authorization, and manpower allocation. Accordingly, it is recommended that its function be extended to encompass the major planning, overall, and master scheduling, as outlined in this paper.

To carry out the objectives of the building program, the Planning (Design), Production, Public Works, and Supply Departments must maintain departmental scheduling groups, working in the closest collaboration with the P. & E. unit. More detailed scheduling, as necessary, can be accomplished at the branch and shop levels. Regular meetings of the key departmental representatives must be held with the top control unit, to consider the progress of each ship. All known delays affecting the work, facilities, manpower, plans, and material must be discussed and means adopted to prevent further difficulties. When necessary, special committees can be formed to investigate any particularly troublesome condition so that a definite and satisfactory solution may be reached. A comprehensive system of progress reporting on all phases of work must be made to the top P. & E. control unit. By operating on the principle of exceptions, immediate attention can be given to items falling behind schedule so that corrective action can be taken.

The use of a standarized classification of work is recommended. It should have the same meaning to all departments and can be based upon the Navy Filing Manual. All estimating, plan design, B/M issue, material procurement, scheduling, progressing, and cost reporting should use the identical terminology of this classification. Each ship can be broken down into a series of erection groups, subdivided as necessary. During the entire course of construction, all work can be controlled through the use of these units. Material should be delivered to the shops or ship in such quantity as to permit working a complete unit at a time. This procedure will greatly simplify the problem of

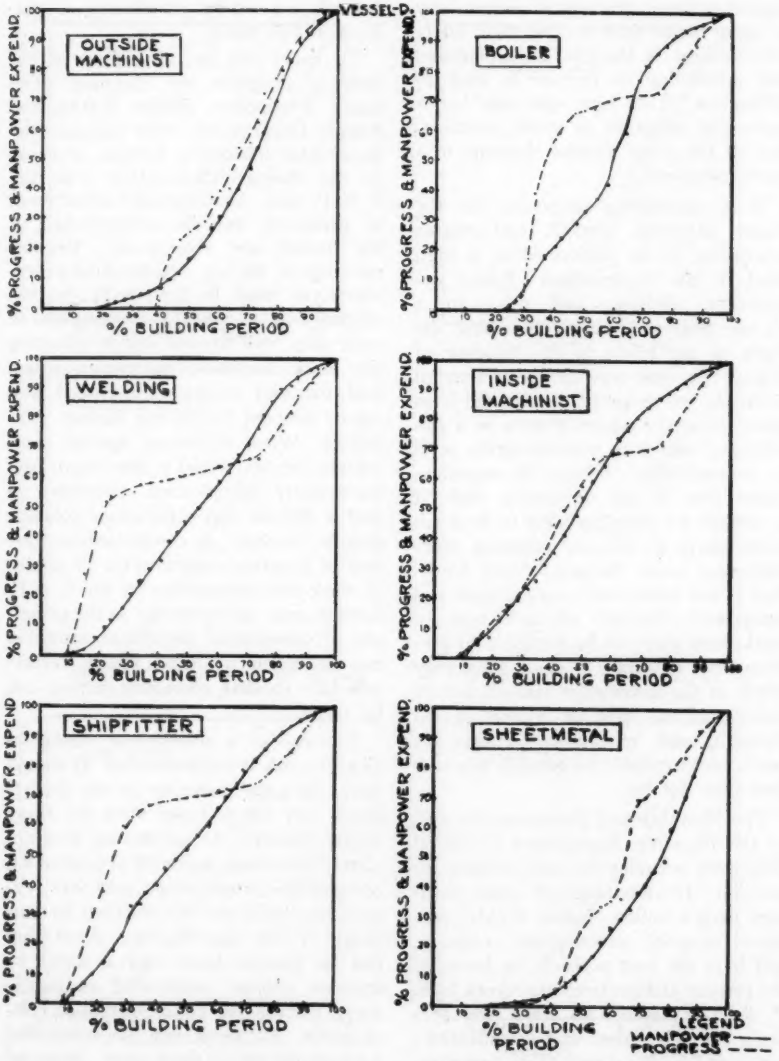


FIGURE 2.—Rate of progress & manpower expenditures for each shop during building period for a CV33 class aircraft carrier.

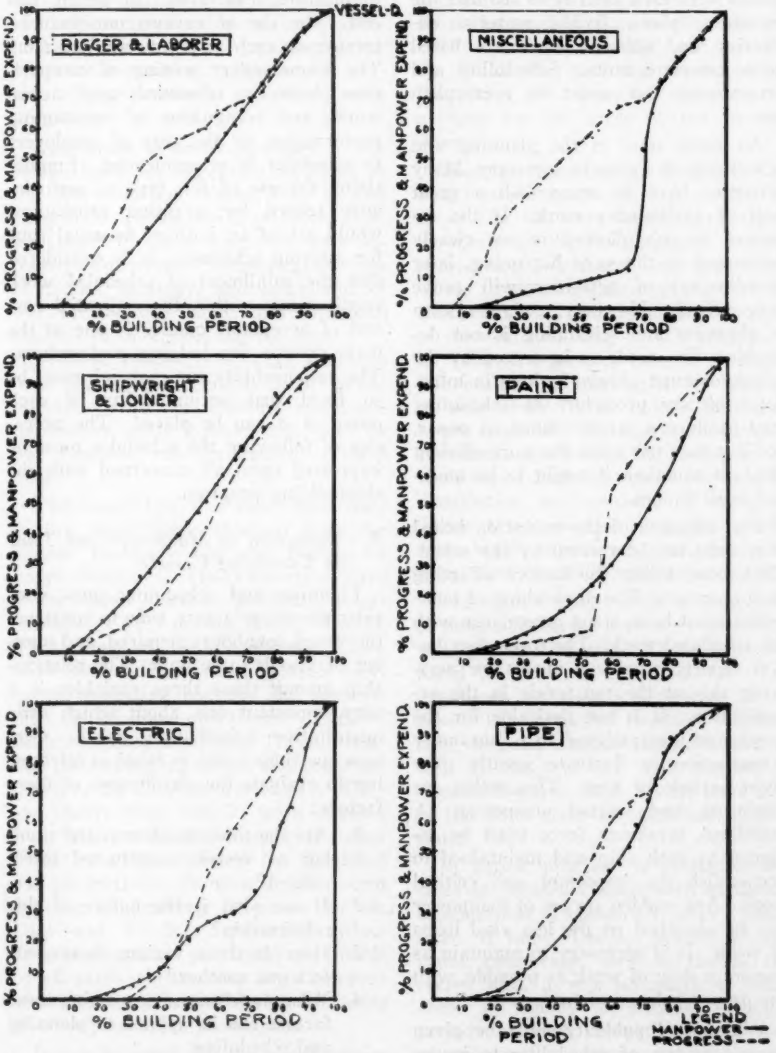


FIGURE 3.—Rate of progress & manpower expenditures for each shop during building period for a CV33 class aircraft carrier.

control. The responsibility must be placed with each activity to see that the estimates, plans, B/Ms, material deliveries, and physical work are based upon complete units. Scheduling and progressing can assist to accomplish this.

An early start in the planning and scheduling of a ship is necessary. Many activities have to accomplish a great deal of preliminary work. If the sequence to be followed is not clearly delineated at the very beginning, later coordination of activities will prove very difficult. However, a rigid system of planning and scheduling is not desirable. The needs to be served by the schedules must always be kept in mind. An arbitrary procedure of scheduling may produce a large volume of paper, but if it does not make for more efficient ship construction, it ought to be modified until it does.

The sequence of the trades on board ship must be determined by the schedulers, considering the factors affecting each operation. The dispatching of manpower must be in strict accordance with the scheduled work. The force distribution reports provide a means for verifying this at the top levels in the organization. It is not desirable for the number of men assigned to a ship under construction to fluctuate greatly over short periods of time. This makes for confusion and wasted manpower. A stabilized, minimum force must be assigned to each ship and maintained to accomplish the important and critical work. Any sudden surges of manpower can be absorbed on the less vital items of work. It is necessary to maintain as smooth a flow of work as possible, with the proper balance of trades.

Widespread publicity must be given to any system of scheduling to insure that all concerned know of its existence, understand the aims, and can govern their work by the schedules. The media of shipyard newspapers, public address systems, work improvement programs, in addition to the usual means of communication, can assist to attain this end. The use of various non-financial incentives, such as commendations from The Commander; posting of comparisons between scheduled and actual work; and recognition of outstanding performance on the part of employees to schedules is recommended. Emphasizing the use of this type of performance record for granting promotions would act as an indirect financial spur for meeting schedules. It is considered that the fulfillment of scheduled work requirements within the estimated cost and of acceptable quality is one of the main criteria for judging performance. The responsibility for each job must be so fixed that accountability of each phase of it can be placed. The necessity of following the schedules must be impressed upon all concerned with the shipbuilding program.

### *B. Reduction in Manpower and Time on Successive Vessels*

Planning and scheduling must consider the three factors, time to construct the vessel, manhours required, and number of vessels to be built. The relationship among these three variables is a very important one, about which little quantitative information exists. Certain questions come to mind in attempting to evaluate the significance of these factors:

1. Are the time, manhours, and number of vessels constructed interrelated?
2. If so, what is the nature of this relationship?
3. How do these various factors affect one another?
4. What conclusions concerning these factors can be applied to planning and scheduling

In an effort to explore this area, use has been made of the concept of operational analysis. This is not new for naval strategy and tactics, but little application to ship construction programs

has been found in the literature. A detailed statistical analysis has been made of the interrelationship of time, manhours, and number of vessels, applying operational analysis, to the escort carrier, destroyer escort, and liberty ship programs.

Operations research provided a scientific basis for executive decisions in the Navy during World War II and since then. In the words of Admiral E. J. King[39, 40], there were two main aspects to this work: "Theoretical analysis of tactics, strategy, and equipment of war on the one hand; and statistical analysis of operations on the other. . . . Operations research, bringing scientists in to analyse the technical import of the fluctuations between measure and countermeasure, made it possible to speed up our reaction rate in several critical cases."

The basic data that have been used in this study were obtained from the Kaiser Company and the Bureau of Labor Statistics. The Vancouver Yard of the Kaiser Company built fifty escort carriers (CVE) during World War II. They were of the Casablanca Class, 6730 tons, and performed valuable service in protecting convoys and supporting amphibious operations. Cutler[41] made this data available. The information concerning manhours and construction time for the destroyer escorts (DE) and liberty ships (EC-2) were obtained from a paper by the Bureau of Labor Statistics (18). Searle[42] has described the productivity changes in the recent wartime shipbuilding programs for the DEs and EC-2s. Substantial reductions in manhours per vessel were made by all yards constructing large numbers of ships of standarized design by means of mass production techniques.

It is to be noted that the escort carrier data were all for one yard, the destroyer escort and liberty ship data were the average of ten and sixteen yards respectively. The time (T) in all cases is expressed in days from keel laying to delivery, manpower (M) required as manhours, while the number (N) of ships for each group is one for the CVE, three for the DE, and ten for the EC-2. The time and manhours for the latter two types of ships is the average for the three or ten in that group.

The first relationship examined was that between manhours and number of ships. The data were fitted into equations by means of the least squares method, considering manhours as dependent. These results, together with the correlation coefficients and the standard errors of the estimates (log of M) are shown in Table 1, equations 1-3. In all cases, the result of an increase in the number of ships built is to reduce the manhours required. The significance of the correlation coefficients and the equations were tested both by means of student's distribution and analysis of variance. These tests revealed that the results were highly significant, statistically, to better than the 0.001 level of probability.

The second relationship of manpower to time, considering manhours dependent was treated similarly. The results are listed in Table 1, equations 4-6. The exponents for time are positive in all cases. It is apparent that this relationship does not explain the manhours as well as the first one with number of ships. However, these results were also of the same order of statistical significance.

In actual practice, it might be desired to construct ships with minimum expenditures of manpower or in a minimum of time. During periods of extreme emergency, such as during the recent war, it was necessary to build ships as rapidly as possible. During periods of keen competition, economy of construction assumes greater importance. Both types of conditions have been analysed in detail. Considering time as the dependant variable, equations 7-9 were obtained with the number of ships, and equations 10-12 with

*Table 1*

| *No.* | *Type* | *Equation* | *Standard error of estimate (Logarithm)* | *Correlation coefficient* |
|---|---|---|---|---|
| 1 | CVE | $M = 2.53 \times 10^6 \times N^{-0.262}$ | 0.0249 | —0.970 |
| 2 | DE | $M = 1.29 \times 10^6 \times N^{-0.215}$ | 0.0386 | —0.892 |
| 3 | EC-2 | $M = 1.14 \times 10^6 \times N^{-0.321}$ | 0.0285 | —0.973 |
| 4 | CVE | $M = 6.54 \times 10^4 \times T^{0.570}$ | 0.0536 | 0.855 |
| 5 | DE | $M = 1.80 \times 10^4 \times T^{0.738}$ | 0.0585 | 0.754 |
| 6 | EC-2 | $M = 3.06 \times 10^4 \times T^{0.725}$ | 0.0279 | 0.974 |
| 7 | CVE | $T = 443 \times N^{-0.351}$ | 0.0771 | —0.868 |
| 8 | DE | $T = 278 \times N^{-0.203}$ | 0.0450 | —0.849 |
| 9 | EC-2 | $T = 133 \times N^{-0.409}$ | 0.0634 | —0.923 |
| 10 | CVE | $T = 2.73 \times 10^{-6} \times M^{1.28}$ | 0.0807 | 0.854 |
| 11 | DE | $T = 8.97 \times 10^{-3} \times M^{0.727}$ | 0.0581 | 0.730 |
| 12 | EC-2 | $T = 1.64 \times 10^{-6} \times M^{1.31}$ | 0.0370 | 0.974 |

manhours. In all cases, the result of an increase in the number of ships is a reduction in the time required. All of these equations proved to be statistically significant to better than the 0.001 level of probability.

The conclusions which can be drawn from the above data are complicated by the effect and interaction of each of the three factors. Therefore, all three have been examined simultaneously by an extension of the statistical techniques of partial and multiple correlation. Considering manpower as dependent, equations 13-15 in Table 2 were obtained by the least squares method.

*Table 2*

| *No.* | *Type* | *Equation* | *Standard error of estimate (logarithm)* | *Mult. correl. coefficient* |
|---|---|---|---|---|
| 13 | CVE | $M = 1.96 \times 10^6 \times T^{0.0413} \times N^{-0.247}$ | 0.0253 | 0.970 |
| 14 | DE | $M = 2.30 \times 10^6 \times T^{-0.102} \times N^{-0.236}$ | 0.0381 | 0.894 |
| 15 | EC-2 | $M = 1.75 \times 10^5 \times T^{0.382} \times N^{-0.165}$ | 0.0148 | 0.993 |
| 16 | CVE | $T = 2.03 \times M^{0.365} \times N^{-0.256}$ | 0.0765 | 0.870 |
| 17 | DE | $T = 2.04 \times 10^3 \times M^{-0.142} \times N^{-0.234}$ | 0.0446 | 0.852 |
| 18 | EC-2 | $T = 3.03 \times 10^{-10} \times M^{1.92} \times N^{0.208}$ | 0.0326 | 0.980 |

*Partial Correlation Coefficients*

| *No.* | *Type* | *(M-N)* | *(M-T)* |
|---|---|---|---|
| 13 | CVE | —0.887 | 0.104 |
| 14 | DE | —0.725 | —0.0119 |
| 15 | EC-2 | —0.845 | 0.852 |
| | | *(T-N)* | *(T-M)* |
| 16 | CVE | —0.312 | 0.0975 |
| 17 | DE | —0.640 | —0.114 |
| 18 | EC-2 | 0.478 | 0.859 |

This set of equations shows the effect of the three factors upon one another. It will be noted that the exponents are all negative for the number of ships and positive for time, except for the DE's, where the latter is negative.

These data reveal that manpower is negatively correlated to a high degree with the number of ships. It is only slightly correlated to time for the CVE (positive) and DE (negative). These equations were all significant or statistically, to better than the 0.001 level of probability. In addition, tests were made by the analysis of variance method to determine whether the equations with three variables were more significant than those of two variables in explaining the variation in manhours. The results indicated that the multiple equations were statistically better than the manhour-time relationship in all cases and better than the manhour-number relationship for the EC-2, to the 0.001 level of probability. The student's distribution t test for the significance of the various partial correlation coefficients revealed that all save the CVE and DE manhour-time coefficients were statistically probable to the 0.001 level

The analysis of the data, considering time as the dependent variable, yielded equations 16-18. It will be noted that the exponents for number of ships were negative for the CVE and DE, but positive for the EC-2. However, the constant had a great negative exponent in this latter case. The manhour exponents were positive for the CVE and EC-2, but negative for the DE. These data reveal the high multiple correlation among the three factors. For the CVE and DE, time is negatively correlated to number. Time is positively correlated to manhours for the CVE and EC-2. These equations were all significant, statistically to better than the 0.001 level of probability.

Tests were made to determine whether the equations with three variables were more significant than those of two in explaining the variation in time. It was found that the multiple equations were statistically more significant than the time-number equation for the EC-2 to the 0.001 level, and better than the time-manhour relationship for the DE to the 0.001 level, for the EC-2 to the 0.005 level, and for the CVE to the 0.03 level of probability. The student's distribution t test for the significance of the various partial correlation coefficients revealed a statistical probability to the 0.001 level for the EC-2 for time-man-hours, while the probabilities of significance for time-number were to the 0.001 level for the DE, 0.006 level for the EC-2, and 0.04 for the CVE.

The various data presented above provide the answers to the questions raised at the beginning of this discussion. It can be conclusively stated that time, manpower, and number of vessels constructed are interrelated. The nature of this relationship is exponential, with the number generally having a negative exponent and time and manpower positive exponents, considering manpower and time as dependent variables. This means that the effect of an increase in the number of ships built is a decrease both in manpower and time. Also, an increase in either time or manpower is generally associated with an increase in the other.

The conclusions which can be drawn from this study are significant. Primarily, as the number of ships built is increased, reductions in both time and manpower can be expected. In doing the necessary planning and scheduling for succeeding vessels, allowances must be made for this reduction. This is a fact which has not always been considered or allowed for in practice. Secondly, if the expected reductions in both time and manpower fail to materialize as the number of ships built increases, it is an immediate sign that something is wrong. It calls for a careful evaluation of the planning, scheduling, work methods, and controls in use.

In estimating the cost and time to construct for a series of identical ships, allowances must be provided for this reduction.

The value of piling manpower on a ship in an effort to reduce the time seems to be of doubtful value. It has been a practice in ship construction to load as many men as possible on board ship to try to complete the ship rapidly when delays occurred. Frequently, the real trouble was lack of plans or material, which held up the proper sequencing of work. The addition of bulk manpower does not aid such a problem and usually hinders efficient construction due to interferences, poor supervision, spread too thin, and the tendency for each man's output to go down when many men are assigned to a job. This is shown by the positive correlation coefficients, M-T and T-M, which were statistically significant.

To gain the maximum both in time and manpower required, it is suggested that any extensive shipbuilding program be so planned that specialization of types of vessels can be made in shipyards. The concentration of one or a few types of vessels in a shipyard allows for the institution of mass production techniques, justifies larger expenditures for jigs, fixtures, special tools, and allows the full benefit of experience to assist in reducing both time and manpower.

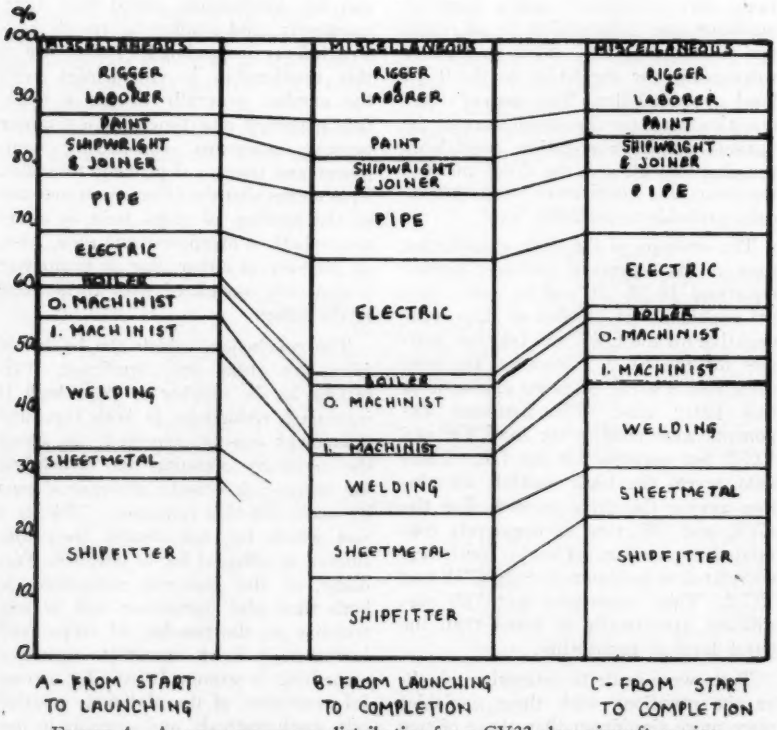


FIGURE 4.—Average manpower distribution for a CV33 class aircraft carrier.

It is not considered wise to stretch the building period of a ship too long because the evidence points to a resulting increase in manpower. For one thing, there is not the same pressure of succeeding trades to get work done. An orderly sequence of work, so arranged that definite tasks are required of each man, with coordination of all trades and careful planning and scheduling of each phase of the work appears to be the best overall plan to obtain the optimum results in time and manpower.

*C. Manpower Analyses*

Analyses of the manpower expenditures by shops for various CV33 class aircraft carriers have been made. While there are differences in the total manpower expended on each ship and in the relative distribution by shops, the data illustrate certain characteristics in the construction of these ships. The average manpower distribution for the five CV33 class aircraft carriers, A-E, from start to launching, launching to completion, and start to completion is shown on Figure 4.

The lead shop in constructing a shop is the shipfitter shop. It required about one fourth of the total manpower. The other trades cannot begin their installations until the structure has been erected and welded. The welding shop was next in magnitude of manpower used, with a ratio approximately one welder to two shipfitters. The electric, rigger and laborer, and pipe shops ranked after the welders in that approximate order. It must be noted that this manpower data is the average of several Yards. A fair approximation for these three shops is 10% of the total manpower expenditures for each.

Following these were the outside machinists and sheetmetal workers, each utilizing around 6½% of the total manpower. The shipwrights and joiners comprised about 5% and 1½% of the total, respectively. Inside machinist work accounted for about 4½% of the total, depending upon the amount of local shop fabrication in place of outside purchase of material. The balance of the work was performed by the paint, boiler, and the miscellaneous shops. Included in the latter category are the forge, sail loft, foundry, and pattern shops.

During the period from start to launching, the shipfitters averaged about 30% of the total manpower, with the welders using about one half that amount. With the riggers and laborers, these shops accounted for more than 55% of the manpower expended prior to launching. About one third of the manpower was expended by the pipe, electric, shipwright, inside machinist, and outside machinist shops combined. The balance was divided among the sheetmetal, paint, boiler, joiner, and miscellaneous shops.

After launching, the shipfitter and welding shops accounted for only about 20% of the total manpower. This was due to the completition of most structural work. The balance of their work after launching consisted of erecting the island, final welding, and certain outfitting. The predominant amount of manpower was expended by the electric shop, about 20% of the total. Others with a large portion of the total manpower consumed were the pipe shop, with 12%, and the rigger and laborer, sheetmetal, and outside machinist shops, with approximately 10% each.

Comparing the manpower expenditures from start through launching with the period from launching through completion reveals that the former period consists mainly of structural erection work while the latter is chiefly outfitting. This is substantiated by the pronounced reduction, on a percentage basis, of the shipfitter, welding, boiler, and shipwright shops from a combined total of over 50% to under 25% after launching. The major outfitting shops, sheetmetal, outside machinist, electric, pipe, and joiner, at the same time, in-

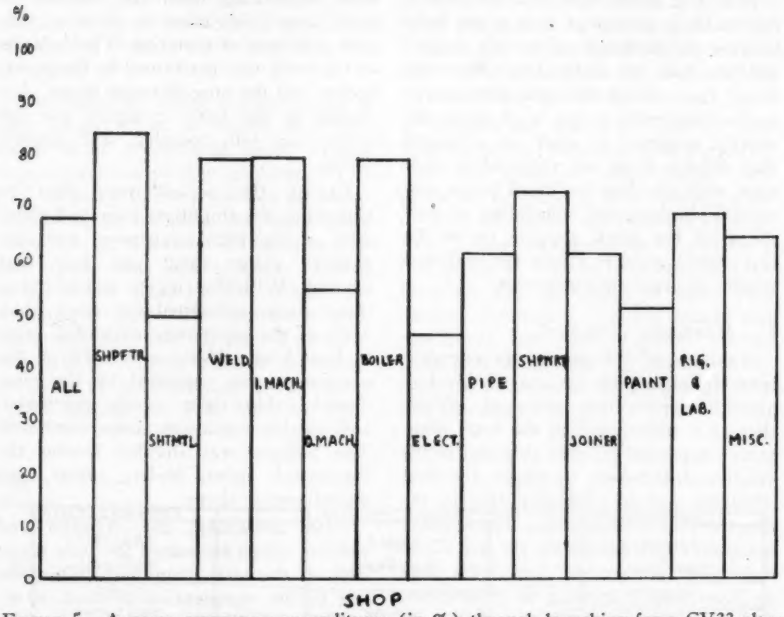


FIGURE 5.—Average manpower expenditures (in %) through launching for a CV33 class aircraft carrier.

creased from a combined total of about 25% to over 50%. The distribution of riggers and laborers remained substantially constant in both periods, about 10%. These two trades service all others, and apparently the amount of assistance is of the same order in both periods. The decline in inside machinist work from 5% to 2.7% after launching points to the completion of most of the shop manufacturing by the time of launching. The percentage of painters doubled after launching, compared to the earlier period of about 3% of the total.

Ships may be launched at various stages of completion. The carriers studied ranged from 58.4% to 79.2% of total manpower expended up to the time of launching, with the average nearly 70%. These data are given in Figure 5, containing a graph of the average manpower expenditures through launching for the CV33 class carriers. The shipfitter and welding shops determine the earliest period when the hull can be waterborne.

At launching, the shipfitter shop had expended a greater proportion of its manpower than any other shop, about 85%. The welding shop had consumed around 80% of its total manpower. The boiler and shipwright shops had also expended 70% to 80% of their manpower by launching. About 80% of the manpower was expended at launching by the inside machine shop. Of the outfitting trades, only the pipe and joiner shops had expended about 60% of their manpower at this period. The electric, sheetmetal, and outside machinist shops, up to launching, had expended approximately 45% to 55% of their total manpower. In analysing this data, the wide

variations in the percentage of outfitting work completed up to launching compared to that for the structural and erection trades is of interest. Thus, for the carriers, shipfitter manpower expended ranged from 74.8% to 92.7%, while outside machinist manpower expended ranged from 38.1% to 73.6%, or double the range. This illustrates the wider variation in amount of outfitting performed prior to launching.

The work of the various shops is performed inside the shop, aboard the ship, or both. For the CV33 class carriers about one quarter of the work was performed inside the shops. The predominantly inside shops were the inside machinists, 100%, and the miscellaneous shops over 90%. The manpower expended inside the shop for the shipfitter shop was about 40%; welding shop, 30%; boiler shop, 25%; pipe and sheetmetals shop, about 20%. The shops which expended most of the manpower aboard ship were the outside machinist, 100%, and the shipwright, electric, rigger and laborer, paint, and joiner shops with approximately 90% each.

The major division in cognizance of work at Naval Shipyards is between hull and machinery. On the basis of manpower expenditures, for carriers, the predominantly hull shops were sheetmetal, shipfitter, shipwright, joiner, paint, and welding. Each of these expended more than 90% of its manpower for hull work. The principal machinery shops were boiler and electric, with about 96% and 86% of their manpower expended for machinery work. The shops whose work was divided, with the hull manpower expenditures listed, were the rigger and laborer, 81%; miscellaneous, 76%; inside machinist and outside machinist, about 60% each; and pipe, approximately 47%. On the overall basis, approximately three quarters of the total manpower was expended for hull work.

Analyses have been made to determine the measures of correlation, by the use of Spearman's rank correlation coefficient, for the five comparable CV33 class carriers, vessels A, B, C, D, and E for the following:

a) total ship cost vs. % of manpower used by shop to total for all shops
b) total ship cost vs. total shop cost for each shop
c) total ship cost vs. % of manpower used to launching to total for each shop
d) individual shop's total cost vs. % of manpower used up to launching to total for each shop
e) total time to construct ship vs. % of manpower used up to launching to total for each shop.

*Spearman's rank correlation coefficient*

| *Shop* | *a* | *b* | *c* | *d* | *e* |
|---|---|---|---|---|---|
| Shipfitter | 0.50 | 0.90 | 0.40 | 0.70 | —0.80 |
| Sheetmetal | —0.10 | 0.60 | —0.10 | —0.80 | —0.70 |
| Welding | —0.10 | 0.90 | 0.20 | 0.10 | —0.90 |
| Inside Machinist | —0.19 | 0.12 | 0.50 | —0.03 | —0.70 |
| Outside Machinist | —0.70 | —0.18 | 0.20 | 0.22 | —0.90 |
| Boiler | 0.62 | 1.00 | 0.10 | 0.10 | —1.00 |
| Electric | 0.80 | 0.90 | 0.20 | 0.10 | —0.50 |
| Pipe | 0.60 | 0.97 | 0.10 | —0.03 | —1.00 |
| Shipwright & Joiner | —0.38 | 0.66 | 0.10 | 0.12 | —1.00 |
| Paint | 0.20 | 0.80 | —0.10 | —0.50 | —0.70 |
| Rigger & Laborer | —0.90 | 0.00 | 0.20 | —0.30 | —0.90 |
| Miscellaneous | —0.90 | —0.79 | —0.50 | 0.72 | —0.60 |
| All | — | — | 0.20 | 0.20 | —0.90 |

In these correlations, a weight of 1 was assigned to the lowest total ship cost, lowest percent of manpower used by shop to total for all shops, lowest total shop cost for each shop, lowest total time to construct ship, and highest percent of manpower used up to launching to total for each shop. Considering the rank correlation coefficients for total shop cost vs. percent of manpower used by shop to total for all shops, a, the electric, boiler, pipe, and shipfitter shops' percentages have the greatest positive rank correlation with the total ship cost. Similarly, the paint, sheetmetal, welding, inside machinist, shipwright and joiner shops' percentages are not very closely related to total ship cost. The rigger and laborer, miscellaneous, and outside machinist shops' percentages were most negatively correlated to total costs. This data is of extreme significance in the control of shipbuilding costs and the distribution of manpower. It seems evident that the main type of control during the construction period ought to be applied to the ratios of electricians, pipefitters, and shipfitters. They seem to have the maximum effect upon total costs of all the major shops.

The total ship cost vs. total shop cost for each shop rank correlation coefficients, b, bear out the conclusion that electric, pipe, and shipfitter shops are the major shops to be controlled, in order to insure low total ship costs. In addition there is a high positive correlation between total costs and boiler, welding, paint, shipwright and joiner, and sheetmetal shops' costs.

There appears to be little significant correlation between the total ship cost and percent of manpower used up to launching to total for each shop, c. The shipfitter and inside machinists are the two shops whose correlation is highest. In the case of shipfitter work, this bears out the contention that it is the shop to watch before launching.

The rank correlation coefficients, d, between individual shop's total costs and per cent of manpower used up to launching to total for each shop, further affirm this close relationship for shipfitter work. Thus, it can safely be concluded from these data, as well as from observation and experience in ship construction, that the shipfitter trade is the critical one prior to launching.

Where speed of construction is important, the data for total time vs. per cent of manpower used up to launching to total for each shop, e, is significant. Thus, it appears that the lower the per cent of manpower expended when the vessel is launched, the sooner will the vessel be completed. It is worth noting that the rank correlation coefficients bear this out for every shop studied. The pipe, shipwright and joiner, boiler, rigger and laborer, outside machinist, welding, and shipfitter shops, especially, have high negative correlations.

The proper ratio of trades to utilize during the construction of a ship is an important problem. Scheduling and manpower analyses together provide the optimum solution to this question. It is considered that the ratios of shipfitters to welders, shipfitters to riggers and laborers, electricians to pipefitters, inside machinists to outside machinists are among the most significant. Accordingly, the ratio of these trades from keel laying (K.L.) to launching (L) to completion (C), and during the total building period (T.B.P.) have been calculated for the carriers. These data are tabulated as follows:

| Trade Ratio | Construction Period | CV 33 Class Aircraft Carriers A | B | C | D | E |
|---|---|---|---|---|---|---|
| a Shipfitters to Welders | K.L. to L. | 1.65 | 1.41 | 2.01 | 2.10 | 2.51 |
| b Shipfitters to Welders | L. to C. | 1.22 | 1.72 | 1.57 | 0.67 | 1.89 |
| c Shipfitters to Welders | T.B.P. | 1.55 | 1.44 | 1.89 | 1.82 | 2.36 |
| d Shipfitters to Rig. & Lab. | K.L. to L | 2.46 | 1.98 | 2.42 | 2.24 | 6.30 |
| e Shipfitters to Rig. & Lab. | L. to C. | 1.05 | 0.91 | 1.22 | 0.54 | 2.38 |
| f Shipfitters to Rig. & Lab. | T.B.P. | 1.96 | 1.77 | 1.94 | 1.82 | 4.77 |
| g Electri's. to Pipef'trs. | K.L. to L. | 1.01 | 0.75 | 0.75 | 0.58 | 1.06 |
| h Electri's. to Pipef'trs. | L. to C. | 0.92 | 1.63 | 1.23 | 2.34 | 1.98 |
| i Electri's. to Pipef'trs. | T.B.P. | 0.97 | 0.96 | 0.98 | 1.01 | 1.50 |
| j In. Mach. to Out. Mach. | K.L. to L. | 1.54 | 0.98 | 1.45 | 0.75 | 0.85 |
| k In. Mach. to Out. Mach. | L. to C. | 0.54 | 0.29 | 0.32 | 0.16 | 0.30 |
| l In. Mach. to Out. Mach. | T.B.P. | 1.09 | 0.80 | 0.75 | 0.51 | 0.53 |

Trade ratios vary somewhat for different trade cognizance patterns in various Yards. Nevertheless, the ratios in the above table have important significance and applications in ship construction. During the prelaunching period, 1.4-2.5 shipfitters are required for each welder; after launching, when most of the structure has been erected, this ratio falls to 0.67-1.9 shipfitters per welder. For the entire building period, the ratio is about 1.4-2.4 shipfitters per welder, since most of the manpower is expended up to launching for these two trades (about 80%).

The ratio of shipfitters to riggers and laborers showed an interesting variance between vessel E and the other four CV33 class carriers. The former had more than twice as many shipfitters to riggers and laborers compared to the other vessels. Prior to launching for vessels A, B, C, and D, 2.0-2.5 shipfitters are utilized compared to one rigger or laborer; after launching the ratio decreases to 0.54-1.2; while the total building period has a ratio of 1.8-2.0 shipfitters per rigger or laborer.

Electricians and pipefitters have also been shown to be critical trades. Their ratio before launching is about 0.58-1.1 electricians per pipefitter; after launching it rises to 0.92-2.3 electricians per pipefitter; during the entire building period the ratio of electricians is about 1.0-1.5 per pipefitter. More pipefitters' work is completed prior to launching than electrical work (61.1% to 46.1%) and that accounts for the increase in the electrical ratio after launching. The pipefitting work begins at the shell of the ship for wing tank flooding and other piping systems, while the electrical work is more extensive on the higher levels of the vessel.

Inside machinist work is heavier than outside machinist work prior to launching than after launching. This is borne out by the trade ratios of 0.75-1.5 inside to outside machinists before launching; 0.16-0.54 after launching; and 0.51-1.1 for the total building period. This ratio could be expected since the machinery and equipment fabricated by the inside machinists is later installed aboard ship by the outside machinists.

The entire problem of the optimum ratio of trades to be assigned during ship construction is a vital one. It is considered that the continued study of this subject would provide data of value in evaluating shipbuilding performance. There seems to be different ratios of trades during the different periods of ship construction. For a given type of vessel, it is felt that there

is a certain trade distribution pattern which is most efficient for the best overall results.

*D. Other Suggestions for Improvement*

There are certain other suggestions for improvement which it is desired to advance. The manpower analyses reveal a wide variation in the distribution of trades aboard ship at different periods. In addition, the number of participating trades is great. These conditions have resulted in difficulty in determining the proper balance among the trades. It has been necessary to keep trained personnel of a wide variety of occupations aboard ship to perform limited amounts of outfitting work. Where there is not a large backlog of work and a steady flow of orders to absorb these diverse trades at all times, layoffs, transfers, and other expedients have to be used. The cost of construction is raised, more supervision is needed, and the resultant overhead is high.

One solution for this problem would be to establish an outfitting trade. The men in this category would be assigned many of the operations which are now spread over several trades. Specifications for this trade have been formulated as follows: Outfitting mechanic. Performs a wide variety of outfitting work, including setting and preparing foundations, installing, aligning, and securing equipment and machinery. Makes necessary piping and electrical connections. Installs brackets, fittings, operating gear, gages, and control devices. Operates, inspects, and tests complete installations and makes necessary adjustments. Checks installation for proper alignment, electrical and piping connections, relief valve settings, operation of gages, and control devices. Installs insulation at pipe and other connections. Attaches label and instruction plates. Does occasional drilling, reaming, tapping, filing, bolting, grinding, tack and seam welding, brazing, cutting, bending, fitting, and touch-up painting of a minor nature required. Works from blueprints, sketches, specifications, and templates. Prepares necessary templates and lays out work. Supervises and directs the work of apprentices, helpers, cranemen, riggers, and laborers.

The type of men selected as outfitting mechanics must be skilled tradesmen, preferably outside machinists or sheet-metal workers. It would be necessary to give them instruction in the essentials of shipfitting, welding, electrical, and pipefitting practice. A period of training for about one year, with three months in each of these categories would be required. A plan such as this would require careful study before its introduction. The only way for it to be successful would be to work out all of its ramifications and then sell the plan to the employees and their unions. The advantages and disadvantages must be fully weighed. No man currently employed at the Yard could be displaced and layed off. Complete acceptance would have to be obtained by the management from all of employees and unions involved. It is only by such careful efforts to obtain the cooperation of all that the harmony and the high morals so necessary for efficient operation can be maintained.

The men who do the planning and scheduling outlined in this paper must be selected with great care. No system of control is better than the men who operate it. The major planning, overall, and master scheduling is considered an industrial engineering function. Engineers, or others with an equivalent background, should be selected to perform this important work. The understanding of the basic principles of planning and scheduling, the ability to visualize a shipbuilding program in its entirety, correlating and coordinating the many diversified and complex elements is required. Several years of experience in ship design, testing, and material procurement, is desirable. A

comprehensive knowledge of the practical aspects of shipbuilding, trade practices, special procedures, and general conditions in the Yard is necessary. The ability to make intelligent estimates of the requirements of work, considering the various factors, and to blend them into a final system of planning and scheduling which is practicable, efficient, harmonious, clear, and orderly is a prime requirement for this position.

The use of models as an aid in establishing the sequence of work and eliminating interferences is recommended. Since shipfitter work is critical before launching and electrical work after launching, it is suggested that these two trades be most carefully controlled through the comparison of actual performance to schedules. Adoption of standards for judging relative progress, such as tonnage erected and finally welded by erection groups and number of circuits installed, connected, and tested, would assist. All compartments ought to be completely outfitted and locked as soon as possible. In general, the manpower on a ship ought to be distributed to allow for completing sections of the ship by decks and areas in a systematic manner. The quality of work performed ought to be held between well defined limits to insure both that the work will be acceptable and that it will not be more exacting than necessary. Close adherence to this principle could reduce the number of rejections, cost, and time of construction.

In summation, the need for careful coordination and control of work must be recognized. It is believed that planing and scheduling which follows these principles will lead to efficient, economical, and rapid ship construction.

### *E. Philosophy of Planning and Scheduling*

It is felt desirable to consider the philosophy underlying planning and scheduling in concluding the Discussion. This philosophy must be clearly understood in order that the approach to the problem and its solution may succeed. The techniques outlined previously must be tempered with the necessary ingredients of patience, understanding, and cooperation. Like all other things, planning and scheduling cannot be rushed, they have their own natural pace. They must be fully understood by all activities in order to be accepted, appreciated, and to function at anywhere near their potential level of benefit. Proper salesmanship is always a necessary adjunct to good planning and scheduling. Full and thorough discussion of the objectives, the means, and the results to be expected will aid immeasurably in selling the ideas and concepts to the operating personnel.

Experience indicates the value of feeling out and preparing the ground for the establishment of planning and scheduling. It is advisable to concentrate on limited objectives at the start. When the effective use of the management tools of planning and scheduling begin to yield the dividends of lower costs, less time to do the work, improved efficiency and morale, and less headaches to the operating personnel, word of this will get around. At that strategic time, the establishment of these controls on a wider basis is indicated.

Once the planning and scheduling section has really taken hold of the situation to gain shipyard-wide acceptance, it is necessary to keep in mind the philosophy which will insure its maintenance and continuing development. A constant interest in the real problems of the various activities, with unceasing effort to solve them, are important adjuncts. Frequently, through understanding, solutions can be reached for problems, when they are studied cooperatively. If plan development is long, difficult, and arduous, perhaps smaller areas can be covered on each plan. If material procurement is faced with difficulties and delays, perhaps partial de-

liveries of the more important parts would help, or, possibly, substitutions can be suggested. If manpower interferences are occurring, perhaps a change in the sequence of doing the work would relieve the situation.

Each activity must be provided full freedom to express its opinions on the procedures and air its objections. Honest consideration must be given to these feelings. Where no planning and scheduling have existed, or where they have been ineffective, the institution of a really workable system will take time. There is a great deal of complex activity to be controlled and coordinated in ship construction. Due allowance must be made for the time required to put the plan into action. It is often a major error to rush the installation of the necessary procedures. The responsibility for building the ship rests with the operating personnel, and so they must have the authority to do the work. At no time does the planning and scheduling section have the right to assume any of this authority of the field activities, without also taking over the responsibility which accompanies it. Since the control agency obviously is unable to build the vessel, it must always keep in mind the philosophic viewpoint that it is there to offer aid to those who do build the ship.

The prevailing attitude of good will, harmonious work relations, high employee morale are all potent factors in achieving the best results from any effort, including planning and scheduling. It is not alone by techniques, no matter how skilled and artful, that work is accomplished. Management must gain the confidence of its employees to succeed in any program or course of action. It is this happy combination of the best scientific methods and excellent personnel relations that yields the optimum returns. This philosophy must always be borne in mind in planning and scheduling work.

## IX. SUGGESTIONS FOR FUTURE STUDY

The author of this paper realizes that while he has endeavored to make a thorough, scientific study of the subject, many problems remain. Accordingly, the following suggestions for future study are made, embracing a research and development program, plan development, material requirements, manpower, and control of work. It is hoped that these suggestions may stimulate additional work to enlarge further the body of knowledge in this field.

### *A. Research and development program*

The shipbuilding industry has embarked upon a basic research program under the sponsorship of the Society of Naval Architects and Marine Engineers [43]. However, the emphasis has been placed mainly on such problems as dynamic loads and fluid mechanics. This paper has attempted to bring to light many of the problems which exist in any ship construction program. A research and development approach, similar to that of the chemical industry, would be extremely valuable in shipbuilding. Basic research techniques and pilot plant developments could be extended to the experimental study of each of the factors of planning and scheduling. Operational analysis would assist immeasurably in evaluating these results. There is a considerable area for research and development in the basic shipbuilding operations, such as structural erection, welding, pipefitting, and material handling. Formalized work simplification studies at the building ways and outfitting piers are indicated in view of the infrequent use of these techniques. Since many compartments on a naval vessel are practically identical, it is suggested that the scientific experimentation include the comparison of different ways of doing the

work in these similar spaces. From this data, the best way of constructing the ship could be evaluated.

*B. Plan development*

The design of a naval vessel is the first step in the shaping of the ship. Experience has indicated the need to study the problem of the sequence of plan issue and the amount of information covered on each plan. Material procurement and the performance of work generally have to await the issue of plans. Accordingly, it is suggested that a study be made of the optimum sequence of ship design. Engineering talent ought to be applied on design development in the order of plan needs by the shipyard as a whole. Furthermore, the amount of data provided on each plan must be studied, to determine whether it is best suited to the end use of that plan. Often, a plan issue is delayed because too wide a scope is covered. The feasibility of issuing plans by erection groups or areas should be determined. The holdups, delays, and alterations on plans require careful study to prevent their occurrence, as far as possible.

*C. Material requirements*

A naval vessel is fashioned from a wide variety of materials, purchased by the shipyard as raw materials, partially fabricated items, and completed assemblies. Material received too early creates storage, deterioration, and other problems, while material received too late may delay the completion of the vessel and certainly interferes seriously with orderly ship erection. Therefore, it is recommended that the subject of material requirements for a naval vessel be studied further, to determine the optimum time in the construction period when each component is needed. It is suggested that the feasibility of extending the amount of shop fabrication and the handling of related groups of material as erection group units also be studied.

*D. Manpower*

The major controllable element of a naval vessel's cost is manpower. Considerable work remains to be done in this field to determine the optimum ratio of trades, supervision, cognizance, and sequence of work, with the results reduced to written standard practice. During 1948 two new shops, Electronics and Temporary Utilities, were established in the Production Department of the Naval Shipyards, bringing the total to nineteen. The problems of control, trade cognizance, trade interference, and stability of employment increase considerably with each new shop. Therefore, it is suggested that a study be made of the optimum number of shops for a Naval Shipyard. One approach to this problem could be the grouping of functionally related shops into five divisions: structural, machinist, electric, pipe, and outfitting. Coincident with this, the establishment of an outfitting trade, previously described, ought to be considered. The performance of men in doing work can be stimulated through the wise use of incentives, both financial and non-financial. The suggestions for future study would be incomplete if they did not include consideration of all phases of incentives. Experimentation ought to be performed in this realm to determine the most effective ones to use.

*E. Control of work*

The primary function of planning and scheduling a naval vessel is to aid in the control of work. Many of the present techniques in use have developed and been maintained without complete scientific evaluation of their merits and comparison to other methods of control. It is suggested that experimentation of all phases of control be performed, to seek out the most effective management devices. The areas to be studied include the planning and scheduling system, production control, cost control, progress measurement, and

reports. At all times, the cost and time of each control must be known and compared to the benefits which it provides. All non-essential controls must be dropped, all ineffective controls strengthened, and all necessary controls provided. Through the establishment of effective controls, management can be given indicating devices to spotlight the efficiency of ship construction.

## X. CONCLUSIONS

It is considered that the following conclusions regarding planning and scheduling a CV33 class aircraft carrier at a Naval Shipyard are warranted, based upon the facts and analyses presented in this paper:

A. There are five phases to planning and scheduling: planning, overall scheduling, master scheduling, detail scheduling, and control. During the pre-keel period, all are commenced and the planning and overall scheduling phases should be completed. During the prelaunching period, master scheduling should be completed. The detail scheduling and control phases are completed during the outfitting period.

B. The principal factors in the five phases of planning and scheduling consist of the following:

1. Planning phase — organization, facilities, manpower, plans, material, and B/Ms.
2. Overall scheduling phase—cardinal dates, control calendar, logical erection groups, overall structural, outfitting, and completion schedule.
3. Master scheduling phase—plans, material, shop fabrication, structure, piping, machinery, electrical, ventilation, outfitting, testing, and painting schedules.
4. Detail scheduling phase—preliminary compartment completion schedule, plan cross index, structure, areas, final compartment completion schedule, weekly summary lists, special spot schedules, and electrical schematics.
5. Control phase—production, cost and progress.

C. Operational analysis has great utility in evaluating shipbuilding programs. Time, manpower, and the number of vessels constructed are interrelated. As the number of ships built increases, both time and manpower are reduced. The concentration of one or a minimum number of vessel types in each shipyard is recommended to obtain the fullest advantage of this reduction, for any extensive shipbuilding program.

D. Management has an immediate signal of trouble when manpower and time reductions do not occur on succeeding vessels. Neither the piling of manpower on a ship nor the stretching of a vessel's building period is effective in reducing time or manpower requirements. Careful planning and scheduling, good methods work, high employee morale, and related aids are the solution.

E. The planning and scheduling function must occupy a relatively high position in the Naval Shipyard organization to be effective. The leaders of this section require an engineering background and an appreciation of the various factors affecting ship construction, for maximum results. The philosophy underlying planning and scheduling requires application of patience, understanding and cooperation. Planning and scheduling cannot be rushed, nor should they be forced upon operating activities. Through analysis of the existing problems and real assistance to the ship's builders, acceptance of the necessary controls can be gained.

F. Realistic scheduling, which considers and takes constructive action, is far superior to the scheduling which as-

sumes that plans, materials, and manpower are available and under control, whereas they may not be.

G. The concept of proper timing of work must be appreciated by all concerned for a shipbuilding program to proceed smoothly. Work starts with the preparation of the estimates and plans for the ship. Delays or incorrect sequences of work at this and succeeding stages exert a cumulative effect later in the program, requiring much more strenuous efforts to correct these conditions. It is entirely feasible to transfer personnel from one section to another in the Design and other Branches to meet scheduled dates and preserve and orderly pattern of work accomplishment.

H. A standarized classification of work and clear definitions of planning and scheduling terminology are aids in coordinating a shipbuilding program. The major components of work for a ship are structure, piping, machinery, electrical, outfitting, ventilation, testing, painting, and miscellaneous.

I. The opportunity exists for increased standardization in shipbuilding. Among the applications are design, workmanship, methods, materials, quality, reporting, and control procedures. Conservation, as an operating principle, can also be profitably employed. Among the applications are work simplification to reduce the physical effort, minimizing of plan alterations to eliminate or diminish ripouts of completed installations, and materials economy and salvage to conserve natural resources.

J. The effect of each new construction ship must be considered in relation to the Yard's overall and individual shops' workloads. Manpower should be brought up to the required level, properly balanced by trades, and maintained, without severe fluctuations or peaks at launching and completion. The establishment of an outfitting trade to perform shipboard outfitting work, including foundations, piping, wiring, and related installations, would minimize standby time, trade interferences, shifting of trades, and generally raise the level of efficiency. The fewer trades that are required on a ship, the better the control, the greater the stability of employment, and the less the cost and time for construction.

K. The major emphasis of control should be applied to the shipfitters before launching, and to the electricians and pipe fitters after launching the vessel. Trade ratios for the different shops vary considerably during the prelaunching and outfitting periods. There are optimum trade distribution patterns for the best overall results.

L. The performance of work must be continuously evaluated by comparison of progress with schedules. Action must be taken to correct deviations which are observed. The most soundly conceived system of planning and scheduling would fail without enforcement of its provisions. The education of all members of the organization in the objectives desired and in the manner of carrying them out is necessary.

M. It is helpful to consider ship construction in terms of areas of the ship which require definite amounts of work. The material for each work unit should be ordered, fabricated, and erected as a complete entity, in preference to working on a piecemeal basis.

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# SYMMETRICALLY FOLDED ANTENNA

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Summary: Properties of the three-wire open ended dipole are discussed qualitatively. Its impedance and broadband characteristics qualify it for use as a transmitting or receiving antenna at a Naval communications station. This type of dipole is eminently suited for use in a television receiving system.

Recently the writer received a letter from Cmdr. G. L. Graveson, USNR, of the Western Electric Company containing brief constructional and operational details of a symmetrically folded antenna he terms a "three wire open ended dipole." It is believed that readers of the "JOURNAL, AMERICAN SOCIETY OF NAVAL ENGINEERS" will be interested in a qualitative discussion of this type of folded dipole as a sequel to the paper "Qualitative Analysis of Folded Dipoles" appearing in the August 1949 issue of the magazine, pages 691 to 697.

The circuit diagram for the three wire open ended dipole is shown in Figure 1. In practice each end of the antenna is supported by an insulator in the form of an equilateral triangle. The spacing between wires is 6 inches for frequencies above 10 mc/sec. and 10 inches for frequencies in the band 3 to

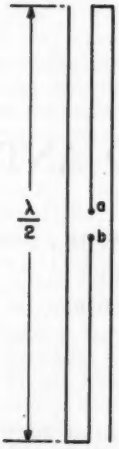



FIG. 1—Isolated "series fed" three wire open ended dipole. Each wire is of the same radius, and the over-all length of the antenna approximates one-half wavelength. The feeding transmission line is connected to the terminals a and b. The magnitude of the input impedance of the antenna is the rms voltage applied across the terminals a and b divided by the rms current flowing at a or b.

10 mc/sec. The distance between insulators (over-all length of the radiating portion of the structure) is estimated from the relation.

Length (in feet) = 468 (feet) divided by frequency (in mc/sec.) The antenna is usually supported in a horizontal position at a distance of about one-half wavelength above the earth's surface.

Cmdr. Graveson points out that when this type of folded dipole is properly installed the magnitude of the input impedance (which is predominantly resistive) approximates 600 ohms. The band width is 7% on both sides of the design frequency for a maximum standing wave ratio on the feeding transmission line of two to one. He reports that he employed this antenna extensively at communication stations he erected in England and elsewhere during the war.

Returning now to Figure 1 it would appear that a qualitative analysis of the "series fed" three wire open ended dipole would be a formidable undertaking, and that a quantitative analysis would be virtually impossible. Actually it turns out that both analyses are relatively simple, but only a qualitative discussion of the way this antenna performs will be given here.

The first step in the solution of the problem is to replace the lower half of the antenna by a large perfectly conducting plane surface (or earth), as shown in Figure 2. This procedure is effective in visualizing the operation of folded dipoles. Provided no auxiliary conductors are located in the vicinity of either antenna, the input impedance of the antenna illustrated in Figure 1 is precisely twice the input impedance of the antenna shown in Figure 2. For purposes of analysis the three wire open-ended dipole has now been replaced by a folded unipole (discussed in the August 1949 issue of JOURNAL, AMERICAN SOCIETY OF NAVAL ENGINEERS in proximity to a base-grounded parasitic element. It is a relatively simple matter to determine quantitatively the input impedance of this antenna by setting up the applicable circuit equations and employing the graphical data now available

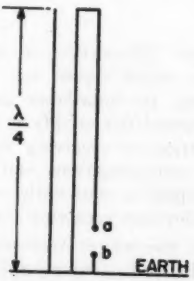



FIG. 2—Two wire folded unipole in proximity to a base-grounded parasite. This antenna is exactly the same as the antenna shown in Figure 1 except that the earth takes the place of one half of the three wire open ended dipole.

in the literature for mutual and self-impedance of close spaced wires. The answer thus obtained, when multiplied by a factor of two, gives the input impedance of an isolated three wire open ended dipole. So much for the quantitative analysis.

To obtain a visual concept of how a folded unipole operates in proximity to a base-grounded parasitic antenna, one notices that the charge distribution along the conductors are similar (at least in magnitude*), for all wires in the antenna are tightly coupled. It is to be observed that large changes in the phase relationship between the magnitude of the charge distribution along the parasitic element and the magnitude of the charge distribution along the folded unipole may be effected by changing slightly the length of the parasite. It is assumed that wires of identical radius are used.

In Figure 3 is sketched the magnitude of the charge distribution along the folded unipole and along the parasitic antenna at an appropriate instant in time. These distributions are similar, so that one might regard the potential of point c to be roughly equivalent to the potential of point d. These two points might well be connected together. The currents flowing along the wires (defined in the previous article as "symmetrical currents") which are effective in setting up the radiation field are not altered significantly by this connection. The "transmission line" current (defined in the previous article as "anti-symmetrical currents") will be changed by use of the shorting bar between points c and d of Figure 3. Fortunately the transmission line component of current is small near the input terminals of

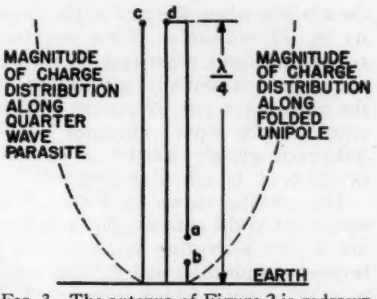



FIG. 3—The antenna of Figure 2 is redrawn. The dotted curves represent the magnitude of the charge distribution along the folded unipole and the parasitic antenna at an appropriate instant in time. Notice that these distributions are similar, so that one might regard the "potential" of point c to be roughly equivalent to the "potential" of point d.

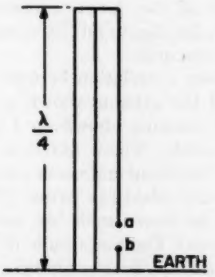



FIG. 4—Three wire folded unipole. By connecting together two points of roughly the same potential, i.e., connecting terminal c to terminal d in Figure 3, one obtains a folded unipole. The fact that current of considerable amplitude may flow in the shorting bar (due to the possible existence of a small potential difference) does not significantly alter the amplitude or phrase of the current flowing at the input terminals a, b, and hence the input impedance of the antenna remains virtually uneffected.

*An antenna which is precisely self-resonant has flowing on its surface one component of current in time phase with the driving voltage. Accordingly there is but one component of charge along such a radiator. An antenna which is not precisely self-resonant (including the anti-resonant case) has two components of current flowing on its surface. One of these is in phase with the driving voltage; the other is in time phase quadrature. It follows that there must be two components of charge along such an antenna also in time phase quadrature. When one speaks of "charge distribution" along an antenna he should be careful to point out what component he is talking about, or whether he is speaking of the charge distribution curve obtained by taking the square root of the sum of the squares of the quadrature components of charge at discrete points along the radiator, as is usually the case.

the antenna when operated in the vicinity of self-resonance. Hence one may regard the input impedance of the antenna to be essentially independent of the antisymmetrical component of current, i.e., the input impedance is not influenced greatly whether c is connected to d, or left open-circuited.

The antenna shown in Figure 4 is equivalent to the antenna shown in Figure 3 when a shorting bar is connected between terminals c and d. The result is a three wire folded unipole which has been discussed in a qualitative way earlier.

Figure 5 shows what might be termed an isolated "shunt excited" three wire folded dipole. It is equivalent to the antenna shown in Figure 4 except that the lower half of the antenna replaces the large conducting plane surface. The reader is reminded that the input impedance of the latter antenna is precisely twice the input impedance of the former antenna.

A direct correlation betwen the properties of the antenna shown in Figure 1 and the antenna shown in Figure 5 is now possible. These antennas, like the writer's beautiful and sweet nine-year-old nieces—are identical twins. Even identical twins have small but insignificant differences! The magnitude of the input impedance of both antennas approximates 600 ohms, a fact that tends to substantiate their kinship.

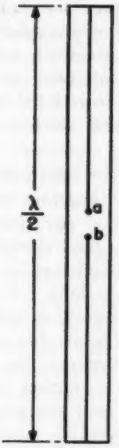
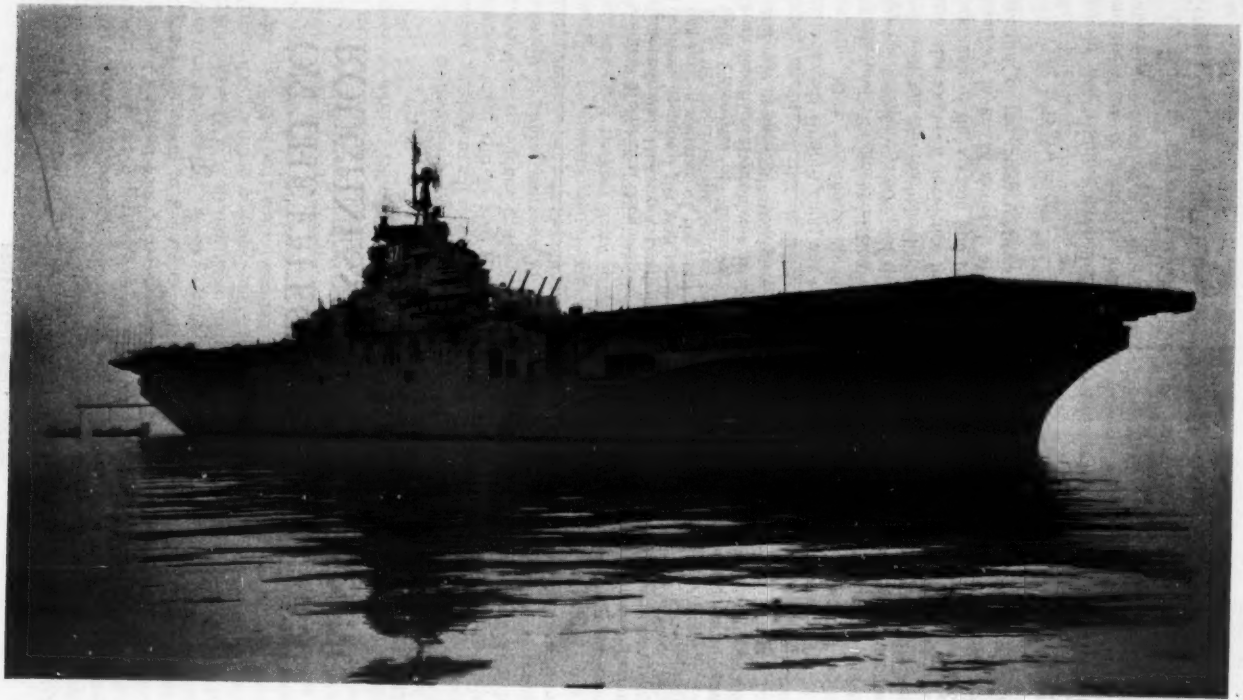



FIG. 5—Isolated "shunt fed" three wire folded dipole. The three wire open ended dipole portrayed by Figure 1 and this antenna are identical twins (which have small but usually insignificant differences). The magnitude of the input impedance to both antennas approximates 600 ohms, a fact which tends to substantiate their kinship.

Dr. Oscar Norgorden, of the U. S. Naval Research Laboratory, who has pioneered in communication antenna development for the Navy concurs in the qualitative analysis presented here for the series excited three wire folded dipole.



A United States Aircraft Carrier

*Official Department of Defense Photo*

# ON THE EFFECTS OF SCALE AND ROUGHNESS ON FREE RUNNING PROPELLERS

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studied Mechanical Engineering and Applied Physics, mainly at the Technical University of Hannover, Germany, from 1919-1925. After several post-graduate courses, he joined the staff of the Hamburg Model Basin in 1927. Since 1948, he has been a member of the staff of the D. W. Taylor Model Basin, Washington, D. C. He received the degrees of Dr. Ing. and of Dr. Ing. habil. from the Technical University of Hannover, Germany. His work is connected with general hydromechanical problems in Naval Architecture, in particular with cavitation and with propeller theory.

Scale and roughness effects on propellers arise from variations of the lift and drag coefficients $c_L$ and $c_D$ of the propeller sections. From investigations on airfoils, it is well known that the lift and drag coefficients of a section of infinite aspect ratio, the angle of incidence being constant, depend on Reynolds number, relative roughness of the section and on the degree of turbulence of the flow outside of the boundary layer. In general, any variation of these independent variables causes a variation of the characteristics of the propeller, i.e., of the curves $k_T = T/\rho\, n^2D^4$, $k_Q = Q/\rho\, n^2D^5$, $\eta = \frac{1}{2}\frac{k_T}{k_Q}\frac{J}{\pi}$ on a base of advance coefficient $J = v_o/nD$. In the case of free running propellers, the variations of Reynolds number and relative roughness are of principal interest and we deal with these two variables in the following.

Attempts to determine these effects by calculation have been published by Kempf [1], van Lammeren [2] and Baker [3].* The papers by Kempf and Baker

* Numbers in [ ]—brackets refer to the bibliography, Numbers in ( )—brackets to equations.

are based on the experimental experience that the $k_T$ (J) curve does not vary, i.e., that the influence on $\eta$ is exclusively due to an influence on the torque. From the geometry of the force components at a propeller section it follows that this assumption holds with zero pitch but, with increasing pitch ratio, the influence increases on $k_T$ and decreases on $k_Q$. The influence on $k_T$ may be small in the case of propellers with moderate pitch but cannot be neglected in principle. There are several other assumptions involved in these investigations, to base, for instance, a part of the calculation on figures deduced from conditions at $T = O$ assuming that all thrust elements are zero in this case [1, 3]. This implies a definite pitch distribution such that the zero lift directions of the sections form a true helical surface. In the paper by van Lammeren, it is assumed that the logarithm of the efficiency, at a fixed advance coefficient, varies linearly with the logarithm of Reynolds number. This assumption is not proved and does not necessarily follow from the fact that the law of friction of a flat smooth plate can be linearly approximated between the logarithms of the frictional coefficient and Reynolds number within a certain interval of the latter.

The writer believes that the following considerations which are based on the airfoil theory of the propeller are less restricted with regard to the underlying assumptions than the methods mentioned above. In the first part of this paper, a simple method is deduced from general propeller equations which enables us to determine the properties of the propeller from the properties of a certain profile of the blade. This method which is sometimes denoted as the method of the "equivalent profile" or of the "propeller polar curve" leads to very simple conclusions on scale and roughness effects if the lift coefficient is not affected when varying Reynolds number or roughness. If both the lift and drag coefficient vary, which happens, for instance, when the characteristics of a full scale propeller are to be determined on a basis of a partially or fully undercritical model, a different method must be applied. Since knowledge of the polar curves of the undercritical sections is required to apply this method as in the aforementioned case and such knowledge is presently lacking, the practical usefulness of the method is doubtful. Therefore, the practical possibilities of calculating scale and roughness effects on propellers are limited to cases where the influence of these effects on the lift coefficient of the sections is zero or can be neglected. This, at the same time, is the necessary assumption for calculating the influence on the drag—coefficient with sufficient accuracy. In such cases, the second method is applied to investigate the influence of a non-uniformly distributed roughness from which a relation follows between the loss in efficiency and the radial extent of roughness at an otherwise smooth blade.

### A. THE METHOD OF EQUIVALENT PROFILE (PROPELLER POLAR CURVE)

The idea of replacing the propeller by one of its profiles, the equivalent profile, and of deducing the properties of the propeller from the simpler properties of this profile traces back to Lock [4] and von Doepp [5] and has been applied to problems of propeller design by Driggs [6] and Kramer [7]. In applying this idea to problems of scale and roughness effects, 3 different steps are necessary. First, the polar curve of the equivalent profile, i.e., its lift and drag coefficient on a basis of angle of incidence, is deduced from the characteristics of the propeller which are known by experiment. Then, the variation of the polar curve with Reynolds number and roughness is considered. Finally, from the polar curve of the varied state, the characteristics of the propeller as affected by scale and roughness are calculated in turn.

Contrary to problems of designing propellers by this method it is necessary in our problem to determine the actual polar curve of the equivalent profile, i.e., it must be certain that the lift and drag calculated from the propeller characteristics are the actual values produced by this profile and do not include any parts from the other profiles. Otherwise, an accurate consideration of the influence of Reynolds number and roughness on the polar curve is not possible because of the different influence of these effects on the different parts. This condition requires the calculations to be made at a definite radius which determines the equivalent profile and which is denoted as the "equivalent radius." As we will see this radius is found from the losses due to profile drag.

a) *Relations between propeller characteristics and propeller polar curve.*

We apply the theory of the moderately loaded propeller, i.e., not allowing for the contraction and the radial pressure gradient in the slipstream. This theory proves sufficiently accurate for design purposes within certain limits of loading and advance coefficient and, hence, can be expected to be sufficient for the reverse problem of a propeller analysis. The theory leads, from the identity of the circulation required by the propeller and produced by the profile, to the relation

$$(1)\quad c_L = 4\,\frac{\pi\,D}{z\,l} \times \frac{\kappa \sin\beta_i \tan(\beta_i - \beta)}{\left[1 - \frac{c_D}{c_L}\tan(\beta_i - \beta)\right]^2}$$

which is satisfied at any radius. Considering the quantity $\frac{c_D}{c_L} \times \tan(\beta_i - \beta)$ small compared with unity, as always possible, the relation is simplified to

$$(2)\quad c_L = 4\,\frac{\pi\,D}{z\,l} \times \kappa \sin\beta_i \tan(\beta_i - \beta)$$

The lift and drag coefficients of the profile elements are related to the thrust and torque elements by:

$$(3)\quad dk_T = \frac{\pi^3}{4}\left(\frac{z\,l}{\pi\,D}\right) c_L\,(x^2 + \lambda^2)\cos^2(\beta_i - \beta)\cos\left(\beta_i + \frac{c_D}{c_L}\right) dx$$

$$(4)\quad dk_Q = \frac{\pi^3}{8}\left(\frac{z\,l}{\pi\,D}\right) c_L \times (x^2 + \lambda^2)\cos^2(\beta_i - \beta)\sin\left(\beta_i + \frac{c_D}{c_L}\right) dx$$

following from the velocity and force diagram at any blade element (Fig. 1), assuming that $\sin\left(\frac{c_D}{c_L}\right) \doteq \frac{c_D}{c_L}$ and $\cos\frac{c_D}{c_L} \doteq 1$.

By means of these 3 relations, 3 equations for the unknown quantities $c_L$, $c_D$, $\beta_i$ exist and, in principle, the unknowns can be determined at any radius as functions of $\lambda$ if the thrust and torque distributions, viz. $\frac{dk_T}{dx}$ and $\frac{dk_Q}{dx}$, are known functions of x. The average factor $\kappa$ which depends on x and $\lambda_i$ is considered known but this quantity need not necessarily equal the values which follow from the Goldstein solution for optimum propellers since $\kappa$ depends also on the distribution of circulation. Hence, the question of the proper values of $\kappa$ is closely connected

with the question of the thrust and torque distribution of a propeller of given shape at a certain advance coefficient. Instead of determining these distributions by more complicated methods which are based on the law of Biot-Savart we will assume reasonably chosen distributions and will show that the final result is almost independent of the particular thrust distribution.

By the assumption of a certain thrust distribution, a factor m which depends on x can be determined in such a way that, at any radius x, the product of the quantity $\frac{dk_T}{dx}$ at this radius and $m(x)$ equals the total thrust coefficient:

$$k_T = \int_{x_n}^{1} \frac{dk_T}{dx}\, dx = \left(\frac{dk_T}{dx}\right)_x m(x)$$

Therefore, from (3) at any fixed value x:

$$(5)\quad k_T = m(x)\ \frac{\pi^3}{4}\left(\frac{z\ 1}{\pi\ D}\right) c_L\ (x^2+\lambda^2)\cos^2(\beta_1-\beta)\cos\left(\beta_1+\frac{c_D}{c_L}\right)$$

By this equation, the assumption of a certain thrust distribution determines, at any radius, a relation between $c_L$ and $c_D$ since $\beta_1$ can be expressed by $c_L$ by means of (2). Having assumed a certain thrust distribution the circulation is determined as a function of x and equation (4) can no longer be considered as an independent equation because both the thrust and torque distribution are related to the circulation. Hence the difficulty of a second independent relation between $c_L$ and $c_D$ arises Lock and von Doepp overcome this difficulty by including the empirical fact that the local efficiency of the sections equals the total efficiency of the propeller with a reasonable accuracy at the radius $x_o = 0{,}7$:

$$(6)\quad \eta_{x_o} = \frac{\lambda}{2}\left(\frac{dk_T}{dk_Q}\right)_{x_o} = \frac{\lambda}{x_o}\,\frac{1}{\tan\left(\beta_1+\frac{c_D}{c_L}\right)_{x_o}} = \frac{J}{\pi\ x_o\ \tan\left(\beta_1+\frac{c_D}{c_L}\right)_{x_o}} = \eta$$

Accepting this equation all considerations are restricted to the radius $x_o$ and the equivalent profile substituted for the propeller is that at $x_o$.

It is certainly an approximation to define the equivalent radius as a constant quantity if a true polar curve of the section at this radius is required. Suppose, for instance, the drag of the profiles near the hub is increased without varying the drag at $x_o$. The efficiency of the propeller decreases slightly, hence, a slightly greater drag for the profile at $x_o$ is calculated although, in reality, the drag of this profile is not varied. At least in principle, the variation of $c_D$ necessitates a variation of the equivalent radius such that the calculated drag coefficient coincides with that of the section at the equivalent radius. Applying (6), no means exist to investigate this variation or, with a fixed value of the equivalent radius, to determine the error of the calculated drag coefficient compared with its true value of $x_o$.

The polar curve $c_D$ and $c_L$ on a basis of $\alpha$ is, by this method, calculated from the known propeller characteristics $k_T$ and $k_Q$ on a basis of J as follows: The sum of angles $\left(\beta_1+\frac{c_D}{c_L}\right) = \left(\beta+\alpha_i+\frac{c_D}{c_L}\right)$ is determined from (6) by

$$(6a)\quad \tan\left(\beta+\alpha_i+\frac{c_D}{c_L}\right)_{x_o} = \frac{J}{\pi\ x_o\ \eta}$$

Eliminating $c_L$ from (2) and (5) a transcendental equation for $\alpha_i$ is obtained. In most cases, it is sufficiently accurate to consider the induced angle $\alpha_i$ small and to put $\cos \alpha_i = 1$, $\tan \alpha_i = \alpha_i$. Then $c_L$ follows from (5):

$$(5a)\quad c_L = k_T \frac{4}{m\,(x_o)\,\pi^3} \left(\frac{\pi\ D}{z\ l_o}\right) \frac{1}{x_o^2 + \lambda^2} \frac{1}{\cos\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)_{x_o}}$$

and $\alpha_i$ from (2):

$$(7)\quad \alpha_i = -\frac{1}{2}\frac{\lambda}{x_o} \overset{+}{(-)} \sqrt{\left(\frac{1}{2}\frac{\lambda}{x_o}\right)^2 + \frac{c_L}{4\ x_o \cos\beta} \frac{z}{\pi} \frac{l_o}{D} \frac{1}{\kappa}}$$

The average factor $\kappa$ depends on $\lambda_i$ which, from the relation

$$\lambda_i = x_o \tan\ (\beta + \alpha_i)$$

depends on the unknown quantity $\alpha_i$, hence, an iteration is necessary to determine $\alpha_i$. With $\alpha_i$, the angle of incidence and the drag coefficient at $x_o = 0.7$ known. It follows from Fig. 1:

$$(8)\quad \begin{cases} \alpha = \psi - (\beta + \alpha_i) \\ \tan \psi = \dfrac{P}{D} \dfrac{1}{\pi\ x_o} \end{cases}$$

Finally

$$\left(\frac{c_D}{c_L}\right)_o = \left(\beta + \alpha_i + \frac{c_D}{c_L}\right)_{x_o} - (\beta + \alpha_i)_{x_o}$$

$$c_{Do} = \left(\frac{c_D}{c_L}\right)_o c_{Lo}$$

In these equations, $\beta$ is determined from

$$\tan \beta = \frac{\lambda}{x_o} = \frac{J}{\pi\ x_c}$$

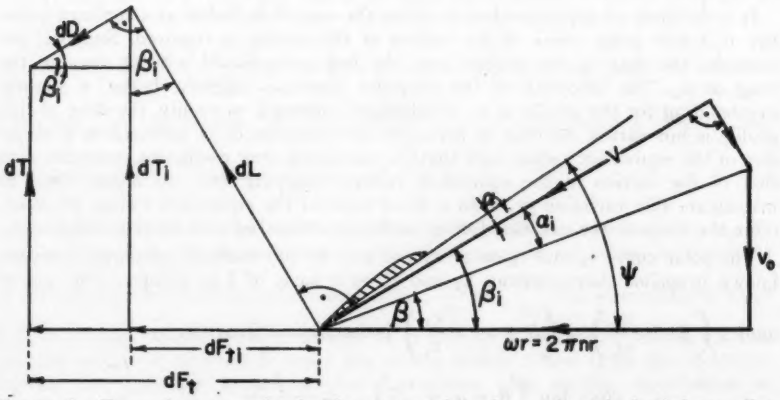


FIGURE 1.—Force-elements and velocities at a section of a moderately loaded propeller.

TABLE 1

*Average factor $\kappa$ at $x_o = 0.75$ for optimum propellers.*

| $z = 3$ | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\frac{1}{\lambda_1}$ | 10 | 5 | 4 | 3 | 2 | 1 | 0 |
| $\kappa$ | 0.980 | 0.884 | 0.827 | 0.738 | 0.611 | 0.466 | 0.390 |
| $z = 4$ | | | | | | | |
| $\frac{1}{\lambda_1}$ | 10 | 5 | 4 | 3 | 2 | 1 | 0 |
| $\kappa$ | 0.994 | 0.939 | 0.893 | 0.825 | 0.710 | 0.554 | 0.477 |

The average factor $\kappa$ which occurs within the above equation for $\alpha_i$ depends on the distribution of circulation as mentioned above but is tabulated only for the optimum distribution (Table 1). From several calculations of this factor in the case of arbitrary thrust distributions, it follows that, around the radius $x_o = 0{,}7$, only slight variations occur as long as all thrust elements are positive. Hence, around this radius, the value of $\kappa$ for optimum propellers can be introduced approximately.

To determine $m(x_o)$ in (5a) a certain thrust distribution is assumed in such a way that the boundary conditions: $k_T = 0$ at $x = 0$ and $x = 1, \frac{dk_T}{dx} = 0$ or $\infty$ at $x = 0$ and $x = 1$ are satisfied and a maximum occurs near the tip. At first, we assume, following Lock, a distribution of the thrust per unit area of the propeller disc, $\frac{dk_T}{dx^2}$, which corresponds to a semi ellipse when plotted on a basis of $x^2$ by which actual distributions are fairly well reproduced. In this case:

$$\frac{dk_T}{dx} = k_T \frac{16}{\pi} x^2 \sqrt{1-x^2}$$

and

$$m(x) = \frac{k_T}{\left(\frac{dk_T}{dx}\right)_x} = \frac{\pi}{16} \frac{1}{x^2\sqrt{1-x^2}}$$

hence

$$m_{0.7} = \frac{\pi}{16} 2.858$$

and the assumed thrust distribution leads to the following relation for $c_L$ at $x_o = 0.7$:

$$(5b)\quad c_{L_o} = k_T \left(\frac{0.230}{\frac{z l_o}{\pi D}}\right) \frac{1}{0.49 + \lambda^2} \frac{1}{\cos\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)_{x_o}}$$

As an alternative, we assume a thrust distribution which corresponds to minimum loss of kinetic energy. For any propeller and any advance coefficient, this assumption can not be satisfied rigorously but is as reasonable an approximation as that chosen by Lock. Only the final results can indicate which assumption should be preferred. Splitting up the efficiency into its components, $\eta_i$ due to kinetic losses and $\eta_\epsilon$ due to profile drag, the following relations exist in this case:

$$(10)\quad \eta_i = \frac{\lambda}{\lambda_i}$$

$$(11)\quad \eta_i = \eta_i\ (c_{Ti},\lambda) \text{ or } \eta_i = \eta_i\ (c_{Pi},\lambda) \text{ resp.}$$

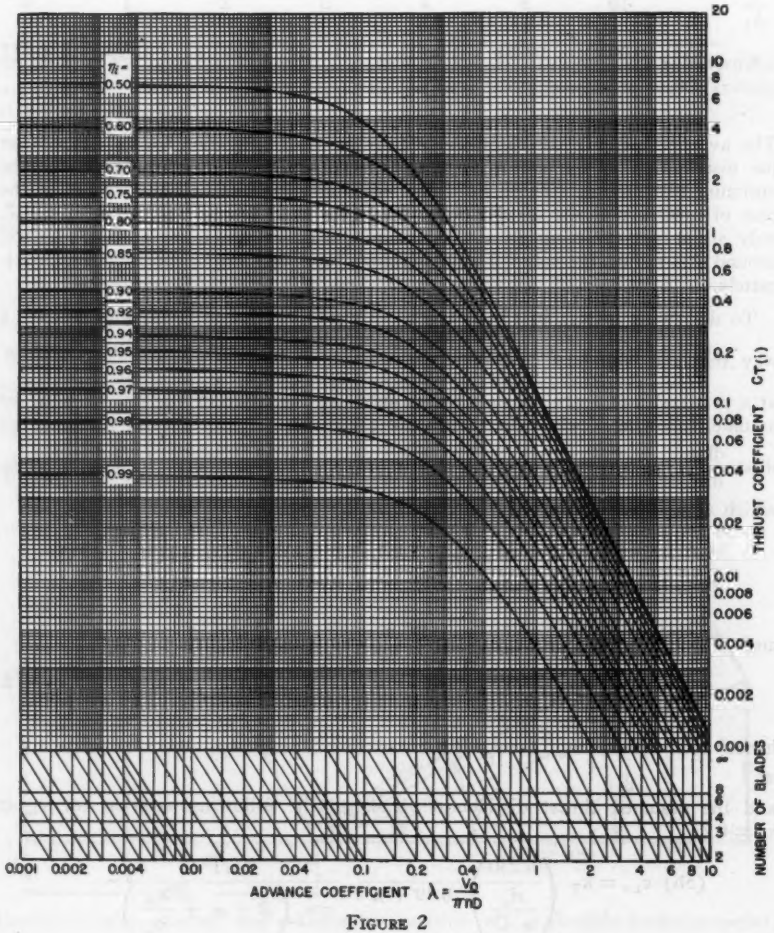


FIGURE 2

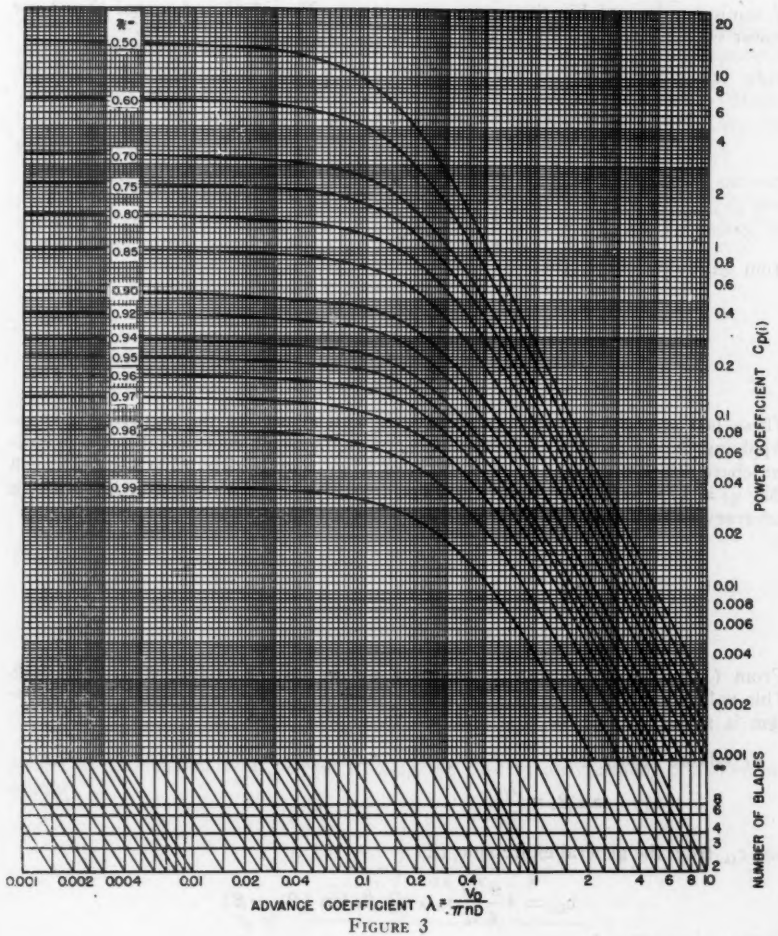


FIGURE 3

In relation (10), $\lambda_1$ is independent of the radius in the case of an optimum propeller. The relations (11) express $\eta_1$ as a function of the ideal thrust loading coefficient $c_{T1} = T_1 \Big/ \frac{\vartheta}{2} \frac{\pi D^2}{4} v_0^2$ or of the ideal power loading coefficient $c_{P1} = P_1 \Big/ \frac{\vartheta}{2} \frac{\pi D^2}{4} v_0^3$ and advance coefficient, $T_1$ and $P_1$ being thrust and power resp. of the propeller in nonviscous fluid. These functions are known by numerical integration and are represented on Figs. 2 and 3 as calculated by Kramer [8]. Due to these known functions the factor $m(x)$ need not be determined

if minimum loss of kinetic energy is assumed. The ideal and actual thrust- or power coefficients resp. are related by the following equations:

$$(12)\qquad c_{Ti} = \frac{c_T}{1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i}$$

$$c_{Pi} = \frac{c_P}{1 + 2/3\left(\frac{c_D}{c_L}\right)_o \frac{1}{\lambda_i}}$$

from which it follows that

$$(13)\quad \eta_\epsilon = \frac{\eta}{\eta_i} = \frac{1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i}{1 + \frac{2}{3}\left(\frac{c_D}{c_L}\right)_o \frac{1}{\lambda_i}}$$

These last expressions are approximations with respect to the numerical factors. Applying these equations to determine $c_L$, $c_D$ and $\alpha$ which correspond to the propeller characteristics $c_T$ and $c_P$ on a basis of $\lambda$ we must satisfy (10) — (13) such that $\eta_i = \lambda/\lambda_i$ equals $\eta_i$ from (11), i.e., from Fig. 2 or 3 resp. Starting with an arbitrary value $\lambda_i$, $\eta_i$ follows from (10) and then, from (13):

$$(13a)\quad \left(\frac{c_D}{c_L}\right)_o = \frac{1 - \frac{\eta}{\eta_i}}{\frac{2}{3}\frac{\eta}{\lambda} + 2\lambda_i}$$

From (12), $c_{Ti}$ or $c_{Pi}$ resp. is obtained and $\eta_i$ follows from Fig. 2 or 3 resp. This value, $\eta_i$, determines by (10) a new value $\lambda_i = \lambda/\eta_i$ with which the calculation is repeated until the first and last value of $\lambda_i$ coincide.

$\beta_i$ follows from:

$$(14)\quad \tan \beta_i = \frac{\lambda_i}{x_o}$$

and $c_{Lo}$ from the general expression (2):

$$c_{Lo} = 4\frac{\pi}{z}\frac{D}{l_o} x_o \kappa \sin \beta_i \tan (\beta_i - \beta)$$

Finally, from Fig. 1:

$$\alpha = \psi - \beta_i, \text{ where } \tan \psi = \frac{P}{D}\frac{1}{\pi x_o}$$

and

$$c_{Do} = \left(\frac{c_D}{c_L}\right)_o c_{Lo}$$

The question arises as to which section, $x_o$, the so determined values of $c_L(\alpha)$ and $c_D(\alpha)$ are attached. In the case of the assumed optimum distribution, equats. (10)—(12) are independent of the radius and equation (2) is valid at any radius, hence, these equations do not require a particular radius. The question can be answered from (13) by which the efficiency $\eta_\epsilon$ of the propeller as a whole is determined from the drag-lift coefficient at a certain radius. On the other hand,

an exact expression for $\eta_\epsilon$ can be deduced which depends on the distribution of $c_D/c_L$ over the radius. Equating both of these expressions for $\eta_\epsilon$ and assuming the distribution of $c_D/c_L$ over x is known then the radius $x_o$ follows at which the drag-lift coefficient leads to an exact value of $\eta_\epsilon$ by means of (13). Hence, at this radius, the values of $c_L$ and $c_D$ calculated by the above method are true profile values.

From this it follows that the equivalent radius is not a constant or a quantity given by the shape of the propeller but depends on the distribution of $c_D/c_L$ over the radius and, as we will see, on the induced rate of advance $\lambda_i$. To deduce the exact value of $\eta_\epsilon$ we refer to Fig. 1 from which follows:

$$c_T = c_{Ti} - \int_{x_n}^{1} \frac{d_{cTi}}{dx} \frac{c_D}{c_L} \tan \beta_i \, dx$$

and

$$c_P = c_{Pi} + \int_{x_n}^{1} \frac{d_{cPi}}{dx} \frac{c_D}{c_L} \frac{1}{\tan \beta_i} \, dx$$

Since

$$\eta_\epsilon = \frac{\eta}{\eta_i} = \frac{c_T}{c_P} \frac{c_{Pi}}{c_{Ti}} = \frac{c_T}{c_{Ti}} \frac{c_{Pi}}{c_P}$$

and

$$\tan \beta_i = \frac{\lambda_i}{x}$$

where $\lambda_i$ is constant with respect to x in the case of an optimum propeller, we obtain:

$$\eta_\epsilon = \frac{1 - \frac{\lambda_i}{c_{Ti}} \int_{x_n}^{1} \frac{d_{cTi}}{dx} \frac{c_D}{c_L} \frac{dx}{x}}{1 + \frac{1}{c_{Pi}\,\lambda_i} \int_{x_n}^{1} \frac{d_{cPi}}{dx} \frac{c_D}{c_L} \times dx}$$

This relation equated to (13) determines the equivalent radius $x_o$ if $\frac{c_D}{c_L}$ is a known function of x. Since this function is not known several functions which comply with practical conditions are assumed and the variation of $x_o$ is investigated.

To find the order of magnitude of this variation it is sufficiently accurate to approximate the optimum distributions of the ideal thrust and power, referred to unit area of the disc, by semi-ellipses on a base of $x^2$. This leads to expressions which can easily be evaluated. From the ellipse with abscissa $x^2$ and ordinate

$\frac{d_{cTi}}{dx^2}$, we obtain corresponding to p. 63.

$$\frac{d_{cTi}}{dx} = \frac{16}{\pi} c_{Ti} \; x^2\sqrt{1-x^2}$$

and analogous:

$$\frac{d_{cPi}}{dx} = \frac{16}{\pi} c_{Pi} \; x^2\sqrt{1-x^2}$$

which are introduced into the last relation for $\eta_\epsilon$. Equated to (13), it follows (15)

$$\left(\frac{c_D}{c_L}\right)_o \frac{\pi}{8}\left(\lambda_i^2 + \frac{1}{3}\right) = \lambda_i^2 \int_{x_n}^{1} x\sqrt{1-x^2}\left(\frac{c_D}{c_L}\right)dx + \int_{x_n}^{1} x^3\sqrt{1-x^2}\left(\frac{c_D}{c_L}\right)dx$$

if the second terms in both the numerators and denominators in the equations for $\eta_\epsilon$ are assumed small as compared to 1 such that second and higher powers can be neglected which is possible in practical cases.

From this relation it follows that arbitrary distributions of $\frac{c_D}{c_L}$ which differ from a constant factor lead to the same value of $x_o$. This implies that the numerical values of $\frac{c_D}{c_L}$ which are assumed when investigating the variation of $x_o$ with a variation of $\frac{c_D}{c_L}$ are less important than the shape of the curve $\frac{c_D}{c_L}$.

The shape of the function $\left(\frac{c_D}{c_L}\right)$ over x is approximated by straight lines which may be different in different intervals of x. Then, in each interval, the integrals in the last relation are of the type $\int_{x1}^{x2} x^m\sqrt{1-x^2}\,dx$ which can be evaluated analytically.

The following 6 distributions of $\frac{c_D}{c_L}$ are considered corresponding to practical cases (Fig. 4):

1.) Straight line decreasing from the hub towards the tip. (I-I-I)
2.) Steeper increase towards the hub from x = 0.4. (II-I-I)
3.) As 2), but increase towards the tip from x = 0.6. (II-I-III)
4.) As 2), but increase towards the tip from x = 0.7. (II-I-IV)
5.) As 3), but less steep increase towards the tip. (II-I-V)
6.) As 3), but increase between x = 0.4 and x = 0.66. (II-VI-III)

The stations $x_o$ for $\lambda_i = 0{,}5$ are calculated as follows:

| Type | $x_o$ |
|---|---|
| 1 | 0.736 |
| 2 | 0.658 |
| 3 | 0.739 |
| 4 | 0.784 |
| 5 | 0.758 |
| 6 | 0.741 |

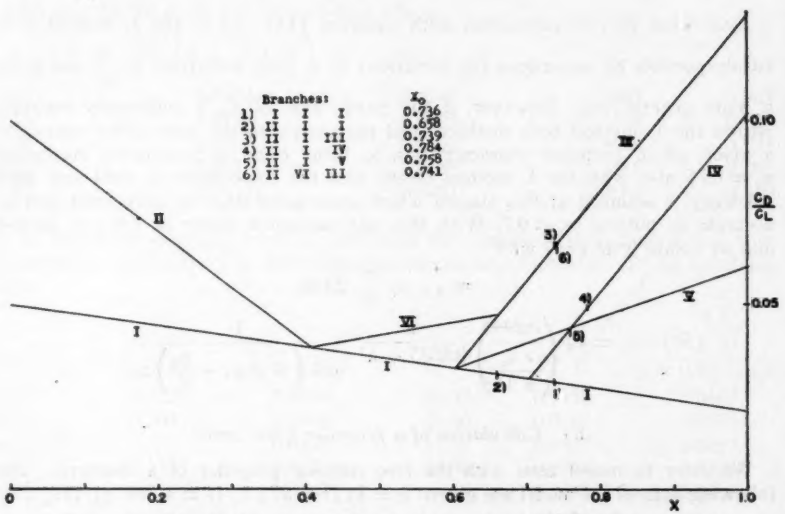


FIGURE 4.—Distribution of drag-lift ratio and position of the equivalent radius

The variation of $x_o$ with $\lambda_1$ is small. If $\lambda_1$ approaches zero, $x_o$ approaches 0.720 for type 1 for instance. Hence, variations with $\lambda_1$ are not taken into account in the following.

From the table it is apparent that, for an accurate determination of $x_o$, a detailed analysis of the propeller with the aim of ascertaining the function $\frac{c_D}{c_L}$ over x is necessary. Further, in an accurate calculation, the variation of $\frac{c_D}{c_L}$ may be such when varying Reynolds number or roughness of the propeller that a variation of $x_o$ occurs. In this case, different equivalent profiles correspond to the original and to the varied state of the propeller and the method becomes questionable since it is based on the known properties of a definite profile. Hence, strictly speaking, the application of the method of the equivalent profile is restricted to such variations of $\frac{c_D}{c_L}$ which differ only from a constant factor.

Considering the above cases 1) - 6), these types differ from a factor which varies greatly with x but it follows that the corresponding variation of $x_o$ is fairly small. It seems possible to replace $x_o$ by a constant quantity such that a reasonable accuracy of $\left(\frac{c_D}{c_L}\right)_o$ is obtained. With the usual shape of propellers, types 6), 5) and 3) are mostly encountered, viz. type 5) with narrow and the types 6) and 3) with wide blades near the tip. From these types, an average $x_o = 0.75$ follows as the equivalent radius. With this value for $x_o$, the error on $\left(\frac{c_D}{c_L}\right)_o$ compared with the value at the actual $x_o$ is fairly small for all types investigated. Hence, the conception of an average equivalent radius which is independent of the distribution $\frac{c_D}{c_L}$ is justified as an approximation.

This holds first in connection with equation (13). As to the 1. method it is hardly possible to investigate the variations of $x_o$ with variations of $\frac{c_D}{c_L}$ and $\lambda_1$ in a more general way. However, if the fixed value of $x_o$ is sufficiently accurate within the 1. method both methods lead necessarily to the same polar curve for a given set of propeller characteristics, $x_o$ being equal in both cases. Assuming $x_o = 0.75$ also with the 1. method means that the coincidence of local and total efficiency is assumed at this station which assumption may be considered just as accurate as putting $x_0 = 0.7$. With this, the numerical factor in (5b) is altered and we obtain from (5a) with

$$m_{0.75} = \frac{\pi}{16}\, 2.688$$

$$(5c)\quad c_{Lo} = k_T \left(\frac{0.244}{\frac{z\, l_o}{\pi\, D}}\right) \frac{1}{0.5625 + \lambda^2}\; \frac{1}{\cos\left(\beta + \alpha_i + \frac{c_D}{c_L}\right) x_o}$$

b) *Calculation of a propeller polar curve.*

We refer to model tests with the free running propeller of a destroyer. The following data of the model are given: $z = 3$; $D = 8''$; $P/D = 1.109$; $(l/D)_{0.75} = 0.489$; $\frac{z\, l_o}{\pi\, D} = \frac{3 \times 0.489}{\pi} = 0.467$; $(d/l)_{0.75} = 0.0309$; $(\tan\psi)_{0.75} = 1.109/\pi\, 0.75 = 0.471$; $\psi_{0.75} = 25.20°$; Mean width ratio $l_{ni}/D = 0.433$.

The result of the model tests, carried out at Reynolds numbers of the equivalent profile $R_{0.75} = \frac{v_o\, D}{\nu} \left(\frac{l}{D}\right)_{0.75} \sqrt{1 + \left(\frac{0.75\,\pi}{J}\right)^2}$ is as follows:

| s | J | $\lambda$ | $k_T$ | $k_Q$ | $\eta$ | $R_{0.75}$ |
|---|---|---|---|---|---|---|
| 0.05 | 1.054 | 0.335 | 0.0683 | 0.0165 | 0.693 | $7.78 \times 10^5$ |
| 0.15 | 0.942 | 0.300 | 0.1168 | 0.0242 | 0.724 | $8.02 \times 10^5$ |
| 0.25 | 0.832 | 0.264 | 0.1648 | 0.0316 | 0.691 | $7.61 \times 10^5$ |
| 0.35 | 0.721 | 0.229 | 0.2115 | 0.0392 | 0.622 | $7.85 \times 10^5$ |
| 0.45 | 0.610 | 0.194 | 0.2582 | 0.0464 | 0.540 | $7.69 \times 10^5$ |

The relation between s, J and $\lambda$ is given by

$$J = \pi\, \lambda = (1\text{-}s)\, \frac{P}{D}$$

To calculate the polar curve from these characteristics of the free running model propeller we start with the 1. method and apply equation (6a), (5c), (7)-(9). First the sum of angles $\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)$ is obtained from (6a):

| s | J | $\eta$ | $\tan\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)$ | $\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)°$ |
|---|---|---|---|---|
| 0.05 | 1.054 | 0.693 | 0.6455 | 32.84 |
| 0.15 | 0.942 | 0.724 | 0.5522 | 28.91 |
| 0.25 | 0.832 | 0.691 | 0.5111 | 27.07 |
| 0.35 | 0.721 | 0.622 | 0.4922 | 26.20 |
| 0.45 | 0.610 | 0.540 | 0.4796 | 25.62 |

With this, the lift coefficient follows from (5c):

| s | $\cos\left(\beta + \alpha_i + \frac{c_D}{c_L}\right)$ | $0.5625 + \lambda^2$ | $k_T$ | $c_L$ |
|---|---|---|---|---|
| 0.05 | 0.8402 | 0.6747 | 0.0683 | 0.063 |
| 0.15 | 0.8754 | 0.6525 | 0.1168 | 0.107 |
| 0.25 | 0.8905 | 0.6322 | 0.1648 | 0.153 |
| 0.35 | 0.8973 | 0.6149 | 0.2115 | 0.200 |
| 0.45 | 0.9017 | 0.6001 | 0.2582 | 0.249 |

To determine $\alpha_i$ and $\lambda_i$ from (7) and from the relation $\lambda_i = x_0 \tan(\beta + \alpha_i)$ an iteration is necessary. The following expressions are known in (7) as functions of s:

| s | $\frac{1}{2}\frac{\lambda}{0.75}$ | $\left(\frac{1}{2}\frac{\lambda}{0.75}\right)^2$ | $\beta^\circ$ | $\cos\beta$ | $\frac{c_L \frac{z\, l_0}{\pi\, D}}{4 \times 0.75 \cdot \cos\beta}$ |
|---|---|---|---|---|---|
| 0.05 | 0.223 | 0.0499 | 24.07 | 0.9130 | 0.0107 |
| 0.15 | 0.200 | 0.0400 | 21.80 | 0.9285 | 0.0179 |
| 0.25 | 0.176 | 0.0310 | 19.39 | 0.9433 | 0.0253 |
| 0.35 | 0.153 | 0.0233 | 16.98 | 0.9564 | 0.0326 |
| 0.45 | 0.129 | 0.0167 | 14.50 | 0.9681 | 0.0400 |

At $s = 0.15$, the following relations exist

$$\alpha_i = -0.200 + \sqrt{0.0400 + \frac{0.0179}{\kappa}}$$

$$\lambda_i = 0.75 \tan(21.80 + \alpha_i)$$

The Goldstein factor $\kappa$ is taken from Table 1 at the respective value $\lambda_i$. We start the iteration with $\lambda_i = \lambda$:

| $\lambda_i$ | $\kappa$ | $\frac{0.0179}{\kappa}$ | $\sqrt{0.0400 + \frac{0.0179}{\kappa}}$ |
|---|---|---|---|
| 0.300 | 0.775 | 0.0231 | 0.251 |
| 0.345 | 0.728 | 0.0246 | 0.254 |
| 0.348 | 0.725 | 0.0247 | 0.254 |

| $\alpha_i$ | $\alpha^\circ_i$ | $(\beta + \alpha_i)$ | $\tan(\beta + \alpha_i)$ | $\lambda_i$ |
|---|---|---|---|---|
| 0.051 | 2.92 | 24.72 | 0.4604 | 0.345 |
| 0.054 | 3.09 | 24.89 | 0.4640 | 0.348 |
| 0.054 | 3.09 | 24.89 | 0.4640 | 0.348 |

In the third line, the first and the last value of $\lambda_i$ coincide. Hence, the result of the iteration at $s = 0.15$ is

$$\alpha_i = 0.054 = 3.09^\circ;\ \lambda_i = 0.348$$

Then from (8) and (9):

$$\alpha = 25.20 - 24.89 = 0.31^\circ$$

$$\frac{c_D}{c_L} = 28.91 - 24.89 = 4.02^\circ = 0.0702;\ c_D = 0.0702 \times 0.107 = 0.00751$$

Proceeding in the same way at the other values of s we obtain the following result for the polar curve of the equivalent profile from the 1. method.

| s | $c_L$ | $c_D$ | $\alpha^o$ | $\lambda_i$ |
|---|---|---|---|---|
| 0.05 | 0.063 | 0.0076 | —0.70 | 0.364 |
| 0.15 | 0.107 | 0.0075 | 0.31 | 0.348 |
| 0.25 | 0.153 | 0.0084 | 1.28 | 0.333 |
| 0.35 | 0.200 | 0.0112 | 2.20 | 0.318 |
| 0.45 | 0.249 | 0.0152 | 3.08 | 0.305 |

In the 2. method, the procedure at each station s is based on equations (12)-(14) and (2). At $s = 0.15$, for instance, the following iteration is carried out, starting with $\lambda_i = \lambda$:

| $\lambda_i$ | $\eta_i = \frac{\lambda}{\lambda_i}$ | $\frac{\eta}{\eta_i}$ | $\left(1 - \frac{\eta}{\eta_i}\right)$ | $\left(\frac{2}{3}\frac{\eta}{\lambda} + 2\lambda_i\right)$ | $\left(\frac{c_D}{c_L}\right)_o$ |
|---|---|---|---|---|---|
| 0.300 | 1.000 | 0.724 | 0.276 | 2.208 | 0.1250 |
| 0.351 | 0.855 | 0.847 | 0.153 | 2.311 | 0.0662 |
| 0.348 | 0.862 | 0.840 | 0.160 | 2.305 | 0.0694 |

| $\left[1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i\right]$ | $k_{Ti}$ | $c_{Ti}$ | $\eta_i$ | $\lambda_i = \frac{\lambda}{\eta_i}$ |
|---|---|---|---|---|
| 0.925 | 0.1263 | 0.362 | 0.856 | |
| 0.954 | 0.1224 | 0.351 | 0.862 | 0.351 |
| 0.952 | 0.1226 | 0.352 | 0.862 | 0.348 |

In this calculation, equation (12) is used in terms of k — coefficients instead of c — coefficients:

$$k_{Ti} = \frac{k_T}{1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i}$$

which is related to $c_{Ti}$ by: $c_{Ti} = \frac{8}{\pi^3 \lambda^2} k_{Ti}$

As result of the iteration, we have determined $\lambda_i = 0.348$, hence, from (14), $\tan \beta_i = 0.348/0.75 = 0.464$ and $\beta_i = 24.90^o$. With this it follows from (2) that:

$$c_L = \frac{4}{0.467} \times 0.75 \times 0.724 \times 0.421 \times 0.0540 = 0.106$$

We obtain further

$$\alpha = 25.20 - 24.90 = 0.30^o$$

and

$$c_D = 0.0694 \times 0.106 = 0.00736$$

Similarly, at the other stations s:

| s | $c_L$ | $c_D$ | $\alpha^o$ | $\lambda_i$ |
|---|---|---|---|---|
| 0.05 | 0.063 | 0.0075 | —0.69 | 0.364 |
| 0.15 | 0.106 | 0.0074 | 0.30 | 0.348 |
| 0.25 | 0.161 | 0.0081 | 1.07 | 0.336 |
| 0.35 | 0.199 | 0.0111 | 2.22 | 0.318 |
| 0.45 | 0.254 | 0.0150 | 2.94 | 0.307 |

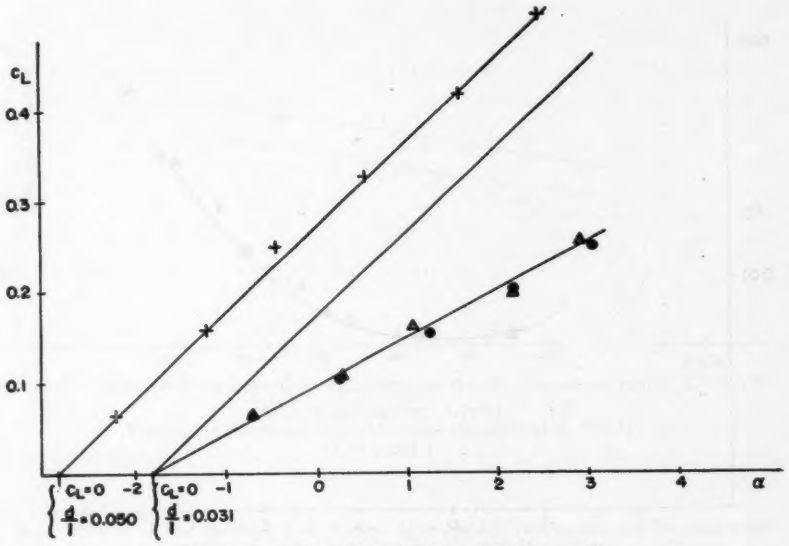


FIGURE 5.—Lift coefficient of the equivalent profile
From propeller test: ● — 1. Method
Δ — 2. "
From test with single airfoil: + $\left(\frac{d}{l} = 0.050\right)$
$(R = 7.8 \times 10^5)$

Both of these methods lead to practically coinciding curves $c_L(\alpha)$ and $c_D(\alpha)$ as shown on Figs. 5 and 6. From this numerical result, it can be said that the assumption of a certain thrust distribution is of secondary importance when calculating the propeller polar curve.

The profiles of the model propeller are ogivals with sharp leading edges. To compare the calculated propeller polar curve with that of an ogival as found from tests in a wind tunnel, for instance, we refer to [3] where polar curves of ogivals of different thickness ratio as determined by Jones and Williams are given for a range of Reynolds numbers. The smallest thickness ratio quoted there amounts to $\frac{d}{l} = 0.050$ whilst, for the equivalent profile, $\frac{d}{l} = 0.031$. Allowing for the thickness difference with respect to the drag coefficient by

$$(c_D)_{0.031} = (c_D)_{0.050} \frac{1 + 2 \times 0.031}{1 + 2 \times 0.050} = (c_D)_{0.050} \times 0.966$$

which follows from considerations stated by Hoerner [9] and with respect to the lift coefficient by shifting the straight line $c_L(\alpha)$ parallel to itself through the angle $\alpha = -\frac{d}{l}$ which is the angle of zero lift of ogivals according to thin airfoil theory we obtain from the tests in a wind tunnel at the Reynolds number $R = 7.8 \times 10^5$ as an average of the propeller test:

| $\alpha^\circ$ | —1.2 | —0.4 | 0.6 | 1.6 | 2.5 | 3.5 |
|---|---|---|---|---|---|---|
| $c_D$ | 0.0089 | 0.0073 | 0.0075 | 0.0097 | 0.0130 | 0.0182 |
| $c_L$ | 0.050 | 0.133 | 0.221 | 0.315 | 0.398 | 0.488 |

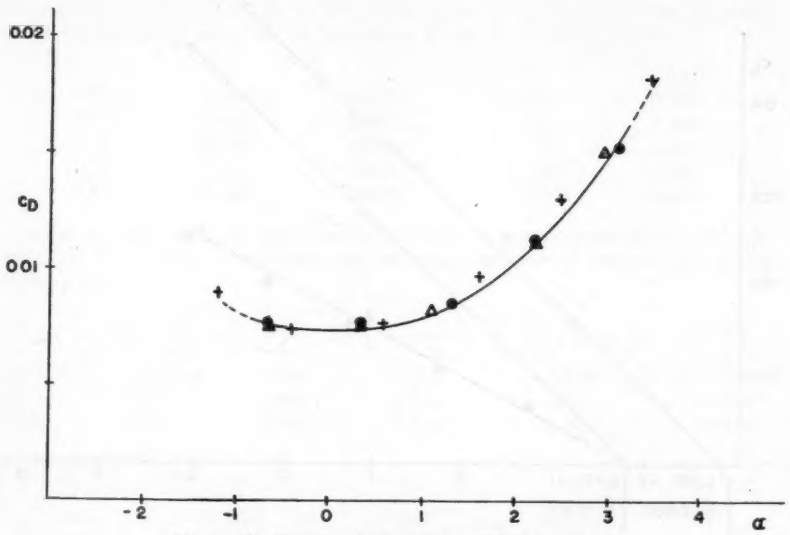


FIGURE 6.—Drag coefficient of the equivalent profile
From propeller test: ● — 1. Method
" " " Δ — 2. "
From test with single aerofoil: +
($R = 7.8 \times 10^5$)

Both of the drag curves (Fig. 6) coincide to a better degree than could be expected taking into account the sensitivity of profile drag measurements and the slight variations of the equivalent radius around $x_o = 0.75$

The slope of the lift curve of the isolated profile is greater than that of the equivalent profile. The reason is that the latter, as a part of a propeller, works in a flow which is curved in such a direction that the lift is smaller for the same angle of attack. From the theory of interference of propeller blades as developed by Ludwieg and Ginzel [10], it follows that the profile at $x_o + 0.75$, in the case of the subject propeller (B.A.R. = 0.663) is affected by the curved flow such that the slope of the lift curve is decreased by the factor 0.55 in the average over $\lambda_1$ (Fig. 7). This theoretical value coincides almost exactly with the lift slope ratio of the equivalent and the isolated profile which amounts to $\frac{0.200}{0.352} = 0.56$. The angle of zero lift of the equivalent profile equals the value from thin airfoil theory viz. $\alpha = -\frac{d}{l} \doteq -1.78°$. Hence, also the lift curve of the equivalent profile is in agreement with the wind tunnel test taking into account the different flow condition at the equivalent profile.

From these results it is concluded that the concept of the equivalent profile is suitable for determining the polar curve of one of the propeller sections from the propeller characteristics. Then scale and roughness effects on the propeller can be calculated from the influence of these effects on this profile.

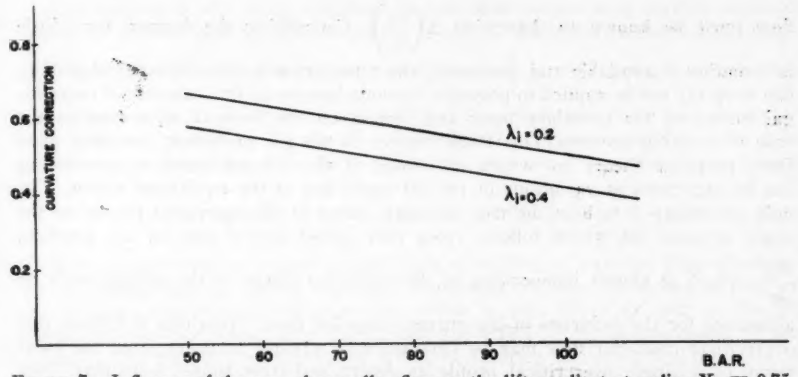


FIGURE 7.—Influence of the curved propeller flow on the lift gradient at radius $X_o = 0.75$
Following Ludwieg - Ginzel
Position of maximum chord length of the blade at $X = 0.75$
$Z = 3$ and 4

(c) *Limits of the method. Calculation of propeller characteristics for different states of the propeller.*

The accuracy of the characteristics to be determined depends on the accuracy with which the true polar curve of the equivalent profile can be calculated. Otherwise, the behavior of the polar curve cannot be predicted when Reynolds number and roughness of the profile vary. This entails restricting the method to overcritical propellers which are characterized as follows. Considering the flow at a section under- and overcritical conditions differ in the relative position of the point of transition from laminar to turbulent boundary layer and of the laminar separation point. With an undercritical section, the transition point is situated behind the laminar separation point and, with an overcritical section, the relative position of the two points is reversed. This explains the separation of the laminar boundary layer in the former case which leads to a high pressure resistance and to a small lift of the undercritical profile. Considering a propeller, the thrust and power elements developed near the hub are small, hence, overcritical propellers permit a limited radial extent of undercritical flow near the hub such that no appreciable effect on the propeller characteristics occurs. With greater radial extent of the undercritical flow the characteristics are affected and the propeller is denoted as an undercritical propeller. Applying the method to such cases, the calculated lift- and drag coefficients of the equivalent profile do not comply with the respective values for the single profile determined from tunnel tests at equal Reynolds number and corrections become necessary to eliminate the influence of the undercritical sections. With respect to the drag coefficient, this is possible, in principle, by (15) from which a relation follows between the variation $\Delta\left(\frac{c_D}{c_L}\right)$ occurring in any interval of x and the corresponding variation $\Delta\left(\frac{c_D}{c_L}\right)_o$ at the equivalent radius. But in this relation, the lift- and drag coefficients of the sections in the undercritical part of the propeller both in under- and overcritical

flow must be known to determine $\Delta\left(\frac{c_D}{c_L}\right)$. Concerning the former, very little information is available and, moreover, the tunnel results for undercritical profiles can probably not be applied to propeller sections because of the influence of centrifugal forces on the boundary layer and, hence, on the laminar separation in the case of rotating sections [11]. With respect to the lift coefficient, no rules exist from propeller theory by which variations of the lift coefficient at any radius can be expressed as variations of the lift coefficient at the equivalent radius. The only possibility is to base the true lift-angle curve of the equivalent profile on the angle of zero lift which follows from thin airfoil theory and on the gradient $\frac{dc_L}{d\alpha}$, which is almost independent of the particular shape of the section, with an allowance for the influence of the curved propeller flow. From this it follows that overcritical characteristics may be obtained with greater accuracy from the polar curve of a single overcritical profile as determined from tunnel tests than from propeller tests with undercritical parts within the polar curve of the equivalent profile.

We come to the conclusion that the application of the propeller polar curve is limited by the critical Reynolds number which, from the above consideration, is determined as that number above which the polar curve of the equivalent profile coincides with that of the isolated profile of equal Reynolds number, allowing for the influence of the curved flow on the lift-angle curve of the latter. To determine this number, the polar curves of methodical series tests have been calculated covering a range of Reynolds numbers from $8 \times 10^4$ to $3.5 \times 10^6$. These numbers refer to $x = 0.7$.

To decide, whether or not a polar curve is overcritical either the point of minimum resistance or the angle of zero lift can be considered. The minimum drag of the profile can be compared with the frictional drag of a flat plate of equal Reynolds number after having introduced corrections for the pressure resistance of the profile and for the influence of the pressure gradient as explained in the following. The propeller test is overcritical if the corrected minimum drag coefficient coincides with the frictional resistance coefficient of a flat plate of equal Reynolds number. Without introducing corrections, the same result can be obtained from the angle of zero lift of the equivalent profile which, in the case of an overcritical propeller, coincides with the zero lift angle as follows from potential theory and which is smaller in the case of an undercritical propeller.

From these evaluations of methodical series propeller tests, it follows that, with sharp nosed sections, the critical Reynolds number $R_{0.7}$ is about $3 \times 10^5$ to $4 \times 10^5$. With rounded noses, the results scatter and the figure could not be determined very accurately.

If these Reynolds numbers have been observed in a model test, the polar curve of a varied state of the propeller can be deduced and then, the propeller characteristics of this varied state can be calculated.

We denote quantities which are referred to a varied state with a prime. In the overcritical range, the lift curve of a section does not vary appreciably with Reynolds number or with moderate roughness, at least not in the range of small lift coefficients concerned, hence, we are justified in writing:

$$(16) \qquad c'_L = c_L$$

With respect to the drag coefficient, a minimum occurs at a certain angle of attack. With thin profiles, this minimum is mainly frictional resistance, the pressure resistance coefficient being of order $0.012\ \frac{d}{l}$ at this point according to measurements by Fage, Falkner and Walker [12] which also show that the minimum pressure resistance is almost independent of Reynolds number with thin profiles and turbulent boundary layer. With this, we write at any angle of incidence:

$$(17)\quad c_D = c_f + c_n = \left[ (c_D)_{Min} - 0.012 \left(\frac{d}{l}\right)_o \right] + c_n,$$

$c_n$ being the pressure resistance at this angle of incidence. Varying Reynolds number and roughness, $c_n$ can be assumed independent of these variations as long as the pressure distribution does not vary which is very likely as long as the lift coefficient does not vary. This means that the effect of the displacement of the potential flow by the boundary layer which is different when varying the state of the propeller is small. Hence, equat. (16) implies

$$(18)\quad c'_n = c_n$$

and we obtain

$$(19)\quad c'_D = c'_f + c'_n = c'_f + \left\{ c_D - \left[ (c_D)_{Min} - 0.012 \left(\frac{d}{l}\right)_o \right] \right\}$$

The difficulty in calculating $c'_D$ from this relation lies in the proper calculation of $c'_f$. Basing this calculation on the known rules of frictional resistance of a flat plate it must be considered that, at the profile, the shearing stresses depend on the pressure distribution and, further, that the transition point from laminar to turbulent flow depends on Reynolds number, pressure distribution, roughness and degree of turbulence of the flow outside of the boundary layer. There are theoretical possibilities of determining approximately the influence of the pressure distribution on the shearing stress [13, 14] and also of determining the dependence of the transition point on Reynolds number in case of smooth surfaces and low turbulence [15]. These methods, in particular the latter, require a great deal of numerical work which is hardly justifiable in connection with the approximate method of the equivalent profile.

From the above mentioned calculations of propeller polar curves in a fairly wide range of Reynolds number, it follows that the frictional coefficient of the equivalent profile is, at greater Reynolds numbers, related to the frictional coefficient of a fully turbulent flat plate $c_{fp}$ in such a way that

$$(20)\quad c'_f = c'_{fp}\left(1 + 2\frac{d}{l}\right),$$

$c'_f$ and $c'_{fp}$ taken at equal Reynolds number.

This approximation which has been suggested by Hoerner [9] implies that the transition point is situated near the stagnation point so that the laminar friction can be replaced by turbulent friction without appreciable error and, further, that the effect of pressure gradient is represented by the factor $\left(1 + 2\frac{d}{l}\right)$. From a fundamental point of view, these approximations are crude but it seems that the frictional resistance of thin sections can be represented by the above relation with sufficient accuracy at high Reynolds numbers and small angles in incidence. If

the velocity distribution at the equivalent profile is known, a more satisfactory approximation would be:

$$(20a) \quad c'_f = c'_{fp} \int \left(\frac{u}{u_o}\right)^2 d\left(\frac{a}{l}\right)$$

where u denotes the velocity at the station a of the section and $u_o$ the relative velocity of the section itself which is $v_o\sqrt{1+\frac{x_o^2}{\lambda^2}}$. The assumptions implied are that the shearing stress is proportional to the square of the local velocity and that the displacing influence of the boundary layer on the potential flow can be neglected. In this calculation, the transition point should be assumed to be coinciding with the point of minimum pressure which corresponds to theoretical results at high Reynolds numbers.

In the following, the approximation (20) is used for full scale propeller sections corresponding to the experience with sections under actual conditions of propeller flow at high Reynolds numbers.

The relations between $c_L$, $c'_L$ and $c_D$, $c'_D$ being known, the propeller characteristics of a varied state can be calculated. We distinguish 2 cases depending on the manner of the distribution of roughness. The first case is referred to a roughness which is uniformly distributed over the entire blade. This case includes the usual problem of calculating scale effect of an overcritical model with respect to a smooth or uniformly roughened full scale. In the second case, which is discussed in B, nonuniform distributions of roughness are considered, the problem, for instance, of determining the effect of roughness concentrated between 2 radii on an otherwise smooth blade.

The equations which govern the influence of Reynolds number and roughness in the first case are obtained as follows on a basis of the propeller polar curve. We start from the approximate relation (2) which must be satisfied at any rate of advance:

$$c'_L = 4\frac{\pi}{z}\left(\frac{D}{l_o}\right) x_o \kappa' \sin\beta'_i \tan(\beta'_i - \beta)$$

$$\text{with } \tan\beta = \lambda/x_o\,,\ \tan\beta'_i = \lambda'_i/x_o$$

Further: $\alpha' = \psi - \beta'_i$ where $\tan\psi = \frac{P}{D}\frac{1}{\pi x_o}$

The known lift-angle curve of the equivalent profile expresses the relation:

$$c'_L = c'_L(\alpha')$$

The quantity $\frac{D}{l_o}$ being known, this set of equations is satisfied if we assume a range of values $\beta'_i$ and determine that angle of incidence $\alpha'$ with which $c'_L$ from (2) and from the polar curve coincide. With $\alpha'$ being known, $c'_L$ and $\beta'_i$ are also known quantities for the respective rate of advance and, further, $c'_D$ follows from (19). Now, the ideal values of the thrust and power coefficient $c_T{}'_i$ and $c_P{}'_i$ can be determined from (10) and (11) such that

$$\eta'_i = \frac{\lambda}{\lambda'_i} = \eta'_i(c'_{Ti}, \lambda)$$

or

$$\eta'_i = \frac{\lambda}{\lambda'_i} = \eta'_i(c'_{Pi}, \lambda)$$

the functions $\eta'_i\ (c'_{Ti}, \lambda)$ and $\eta'_i\ (c'_{Pi}, \lambda)$ being known in the assumed case of minimum loss of kinetic energy (Fig. 2 and 3). Finally, the thrust and power coefficients and the efficiency in the varied state of the propeller follow from (12):

$$c'_T = c'_{Ti}\left[1 - 2\left(\frac{c_D}{c_L}\right)'_o \lambda'_i\right]$$

$$c'_P = c'_{Pi}\left[1 + \frac{2}{3}\left(\frac{c_D}{c_L}\right)'_o \frac{1}{\lambda'_i}\right]$$

$$\eta' = \frac{c'_T}{c'_P}$$

By the above procedure, $\lambda'_i$ is determined from equations which are independent of $\left(\frac{c_D}{c_L}\right)_o$ i.e., $\lambda_i$ does not vary with a variation of $\left(\frac{c_D}{c_L}\right)_o$ as long as the lift-angle curve does not vary. Hence, if $c'_L(\alpha') = c_L(\alpha)$, implying that the polar curve is based on a test with a turbulent boundary layer over the entire blade, and if the approximation

(2) holds, i.e., if $\left[1 - \frac{c_D}{c_L}\tan(\beta_i - \beta)\right]^2 \doteq 1$, then it follows that:

$$\lambda'_i = \lambda_i$$

and

$$\eta'_i = \frac{\lambda}{\lambda'_i} = \frac{\lambda}{\lambda_i} = \eta_i$$

We obtain the result that, under the 2 conditions just mentioned, the propeller is affected by Reynolds number and roughness in such a way that the ideal efficiency remains constant and, as a consequence, that the velocity diagram, Fig. 1, does not vary. Since the ideal thrust and power coefficients, $c_{Ti}$ and $c_{Pi}$, are functions of $\eta_i$ and $\lambda$, these quantities also remain constant with variations of $c_D$. From this follows the influence of Reynolds number and roughness on the propeller characteristics determined by:

$$(21)\left\{\begin{array}{l}
\eta' = \eta_i\,\eta'_\epsilon = \eta\,\dfrac{\eta'_\epsilon}{\eta_\epsilon} \\[2ex]
\eta_\epsilon = \dfrac{1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i}{1 + \frac{2}{3}\left(\frac{c_D}{c_L}\right)_o \frac{1}{\lambda_i}},\quad \eta'_\epsilon = \dfrac{1 - 2\left(\frac{c'_D}{c_L}\right)_o \lambda_i}{1 + \frac{2}{3}\left(\frac{c'_D}{c_L}\right)_o \frac{1}{\lambda_i}} \\[2ex]
k'_T = k_{Ti}\left[1 - 2\left(\frac{c'_D}{c_L}\right)_o \lambda_i\right] = k_T \dfrac{1 - 2\left(\frac{c'_D}{c_L}\right)_o \lambda_i}{1 - 2\left(\frac{c_D}{c_L}\right)_o \lambda_i} \\[2ex]
k'_Q = k_{Qi}\left[1 + \frac{2}{3}\left(\frac{c'_D}{c_L}\right)_o \frac{1}{\lambda_i}\right] = k_Q \dfrac{1 + \frac{2}{3}\left(\frac{c'_D}{c_L}\right)_o \frac{1}{\lambda_i}}{1 + \frac{2}{3}\left(\frac{c_D}{c_L}\right)_o \frac{1}{\lambda_i}}
\end{array}\right.$$

In this way, a simple determination of the propeller characteristics in a varied state becomes possible from the polar curve of the equivalent profile. To give an example, we refer to the polar curve of the model test quoted in b) and calculate the influence of Reynolds number on the corresponding smooth full scale propeller ($D = 110''$, $v_s = 35$ knots).

From the curve $c_D(\alpha)$, Fig. 6, a minimum of about 0.0073 is obtained, hence, from (17), for any value of s:

$$c_n = c_D - 0.0073 + (0.012 \times 0.0309) = c_D - 0.0069$$

With this we obtain the following table from (19) and (20), taking $c_D$ from the average curve on Fig. 6 at the average value of $\alpha$ from both of the methods:

| s | $c_D$ | $c_n$ | $R'_{0.75}$ | $c'_{fP}$ | $1.062\, c'_{fP}$ | $c'_D$ |
|---|---|---|---|---|---|---|
| 0.05 | 0.0079 | 0.0010 | $5.47 \times 10^7$ | 0.0046 | 0.0049 | 0.0059 |
| 0.15 | 0.0074 | 0.0005 | $6.02 \times 10^7$ | 0.0046 | 0.0049 | 0.0054 |
| 0.25 | 0.0082 | 0.0013 | $6.71 \times 10^7$ | 0.0045 | 0.0048 | 0.0061 |
| 0.35 | 0.0112 | 0.0043 | $7.64 \times 10^7$ | 0.0044 | 0.0047 | 0.0090 |
| 0.45 | 0.0150 | 0.0081 | $8.92 \times 10^7$ | 0.0043 | 0.0046 | 0.0127 |

In this table $R'_{0.75} = \frac{v'_o D'}{\nu'} \left(\frac{l_o}{D}\right) \sqrt{1 + \left(\frac{0.75\,\pi}{J}\right)^2}$

and $c'_{fP}$ is taken from the formula by Prandtl-Schlichting: $c'_{fP} = 2 \times 0.455/(\log R')^{2.58}$.

The characteristics of the full scale propeller are deduced from those of the model by (21) which formulae lead to the following tables, $c'_L$ taken again from the average curve at the average value of $\alpha$:

| s | $c'_D$ | $c'_L = c_L$ | $\frac{c'_D}{c_L}$ | $\frac{c_D}{c_L}$ |
|---|---|---|---|---|
| 0.05 | 0.0059 | 0.075 | 0.0786 | 0.1053 |
| 0.15 | 0.0054 | 0.107 | 0.0504 | 0.0692 |
| 0.25 | 0.0061 | 0.158 | 0.0386 | 0.0519 |
| 0.35 | 0.0090 | 0.210 | 0.0428 | 0.0533 |
| 0.45 | 0.0127 | 0.250 | 0.0508 | 0.0600 |

| $\lambda'_i = \lambda_i$ | $\frac{1 - 2\frac{c'_D}{c_L}\lambda_i}{1 - 2\frac{c_D}{c_L}\lambda_i}$ | $k_T$ | $k'_T$ |
|---|---|---|---|
| 0.360 | 1.021 | 0.0683 | 0.0697 |
| 0.350 | 1.014 | 0.1168 | 0.1184 |
| 0.335 | 1.009 | 0.1648 | 0.1663 |
| 0.318 | 1.007 | 0.2115 | 0.2130 |
| 0.306 | 1.006 | 0.2582 | 0.2597 |

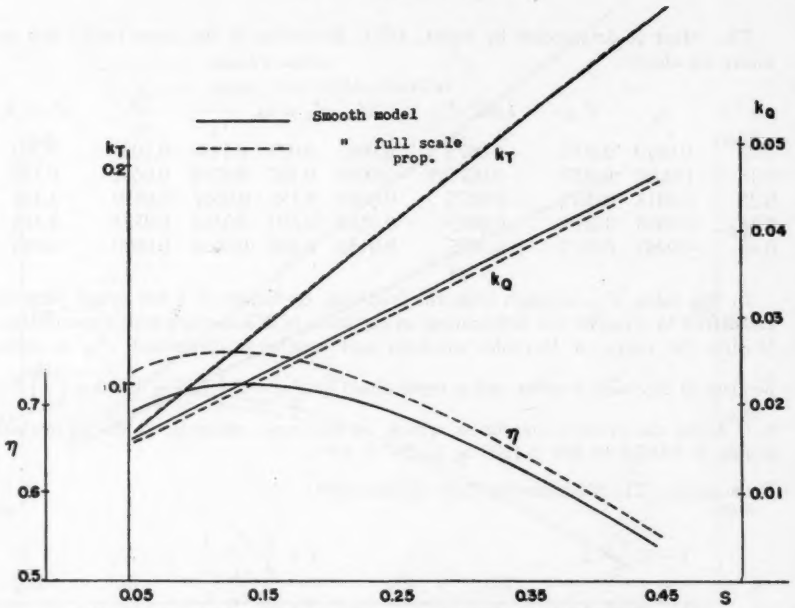


FIGURE 8.—Scale effect of a smooth model ($R_{0.7} = 7.5 \cdot 10^5$ Average) with respect to a smooth full Scale propeller ($R_{0.7} = 5.2 \div 8.5 \cdot 10^7$)

| s | $\frac{1+\frac{2}{3}\frac{c'_D}{c_L}\frac{1}{\lambda_i}}{1+\frac{2}{3}\frac{c_D}{c_L}\frac{1}{\lambda_i}}$ | $k_Q$ | $k'_Q$ | $\eta$ | $\frac{\eta'_\epsilon}{\eta_\epsilon}$ | $\eta'$ |
|---|---|---|---|---|---|---|
| 0.05 | 0.959 | 0.0165 | 0.0158 | 0.693 | 1.065 | 0.738 |
| 0.15 | 0.968 | 0.0242 | 0.0234 | 0.724 | 1.048 | 0.759 |
| 0.25 | 0.976 | 0.0316 | 0.0308 | 0.691 | 1.034 | 0.715 |
| 0.35 | 0.980 | 0.0392 | 0.0384 | 0.622 | 1.028 | 0.639 |
| 0.45 | 0.981 | 0.0464 | 0.0455 | 0.540 | 1.025 | 0.554 |

The result of these calculations is represented on Fig. 8. At equal s, both the thrust and torque coefficient are affected by the increasing Reynolds number, the latter to a greater extent than the former. At $s = 0.225$ which corresponds to the advance coefficient at $V_s = 35$ knots, the percentage variations amount to: $\frac{\Delta k_T}{k_T} = 0.9\%$; $\frac{\Delta k_Q}{k_Q} = -2.7\%$; $\frac{\Delta \eta}{\eta} = 3.7\%$.

Next, the combined effect of Reynolds number and roughness is considered, viz. the characteristics of a rough full scale propeller are deduced from a test with a smooth overcritical model. For the roughness, we assume an equivalent sand roughness $k_s = 0.001''$ which, following Baker [3], corresponds to an unworked bronze surface).*

)* This figure can only be considered as an order of magnitude. According to Kempf [1], $k_s = 0.001''$ corresponds to a bronze surface which is ground in the usual way without polishing.

The effect is determined by equat. (21). Referring to the same model test as above we obtain:

| s | $c_n$ | $c'_{fP}$ | $1.062\,c'_{fP}$ | $c'_D$ | $c'_L = c_L$ | $\frac{c'_D}{c_L}$ | $\frac{c_D}{c_L}$ | $\lambda'_i = \lambda_i$ |
|---|---|---|---|---|---|---|---|---|
| 0.05 | 0.0010 | 0.0071 | 0.0075 | 0.0085 | 0.075 | 0.1133 | 0.1053 | 0.360 |
| 0.15 | 0.0005 | 0.0071 | 0.0075 | 0.0080 | 0.107 | 0.0748 | 0.0692 | 0.350 |
| 0.25 | 0.0013 | 0.0071 | 0.0075 | 0.0088 | 0.158 | 0.0557 | 0.0519 | 0.335 |
| 0.35 | 0.0043 | 0.0071 | 0.0075 | 0.0118 | 0.210 | 0.0562 | 0.0533 | 0.318 |
| 0.45 | 0.0081 | 0.0071 | 0.0075 | 0.0156 | 0.250 | 0.0624 | 0.0600 | 0.306 |

In this table, $c'_{fP}$ is taken from the frictional coefficient of a flat rough plate as calculated by Prandtl and Schlichting on the basis of Nikuradse's pipe experiments. Within the range of Reynolds numbers and roughness concerned, $c'_{fP}$ is independent of Reynolds number and is represented by $c'_{fP} = 2\left(1.89 + 1.62 \log \frac{1}{k_s}\right)^{-2.5}$, $k_s/l$ being the relative roughness which, in this case, amounts, at the equivalent profile, to $0.001/\ (0.489 \times 110) = 1/(5.4 \times 10^4)$.

From equat. (21) the following table is calculated:

| s | $\frac{1 - 2\frac{c'_D}{c_L}\lambda_i}{1 - 2\frac{c_D}{c_L}\lambda_i}$ | $k_T$ | $k'_T$ | $\frac{1 + \frac{2}{3}\frac{c'_D}{c_L}\frac{1}{\lambda_i}}{1 + \frac{2}{3}\frac{c_D}{c_L}\frac{1}{\lambda_i}}$ | $k_Q$ | $k'_Q$ |
|---|---|---|---|---|---|---|
| 0.05 | 0.994 | 0.0683 | 0.0679 | 1.013 | 0.0165 | 0.0167 |
| 0.15 | 0.996 | 0.1168 | 0.1163 | 1.010 | 0.0242 | 0.0244 |
| 0.25 | 0.998 | 0.1648 | 0.1645 | 1.007 | 0.0316 | 0.0318 |
| 0.35 | 0.998 | 0.2115 | 0.2111 | 1.005 | 0.0392 | 0.0394 |
| 0.45 | 0.999 | 0.2582 | 0.2579 | 1.004 | 0.0464 | 0.0466 |

| s | $\eta$ | $\frac{\eta'_\epsilon}{\eta_\epsilon}$ | $\eta'$ |
|---|---|---|---|
| 0.05 | 0.693 | 0.981 | 0.680 |
| 0.15 | 0.724 | 0.986 | 0.714 |
| 0.25 | 0.691 | 0.991 | 0.685 |
| 0.35 | 0.622 | 0.993 | 0.618 |
| 0.45 | 0.540 | 0.995 | 0.537 |

By the roughness assumed, the torque coefficient of the full scale propeller is slightly increased compared with the smooth model and the thrust coefficient is slightly decreased (Fig. 9). Comparing the rough and smooth full scale propellers at $s = 0.225$, the loss in efficiency amounts to $(-4.5\%)$. The following table shows the results at $s = 0.225$ obtained so far:

| | $k_T$ | $k_Q$ | $\eta$ |
|---|---|---|---|
| Model | 0.1520 | 0.0297 | 70.0 |
| Smooth full scale | 0.1534 | 0.0289 | 72.6 |
| Rough full scale | 0.1515 | 0.0299 | 69.3 |

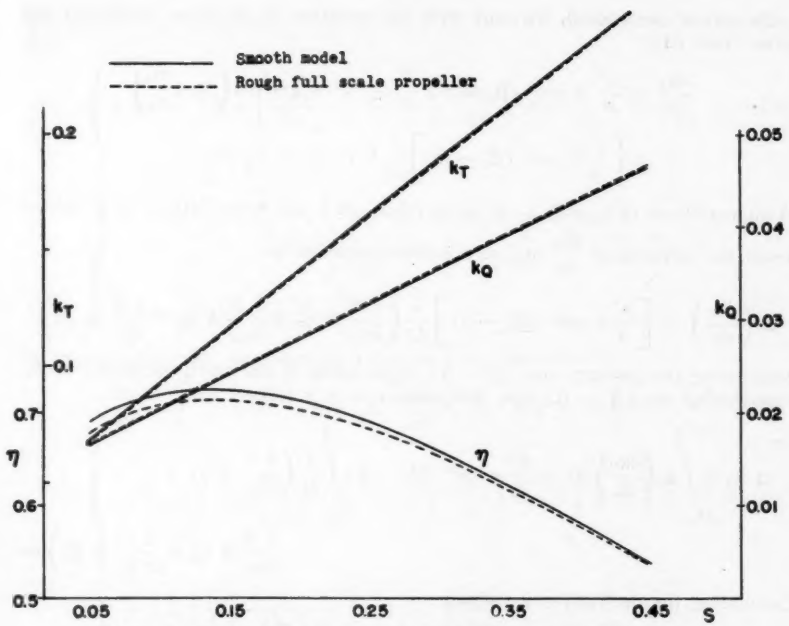


FIGURE 9.—Scale effect of a smooth model ($R_{0.7} = 7.5 \cdot 10^5$ Average) With respect to a rough full Scale propeller ($R_{0.7} = 5.2 \div 8.5 \times 10^7$; $k^1{}_s = 0.001''$)

## B. INTEGRAL METHOD

It has been pointed out that the method of the propeller polar curve is limited to overcritical propellers when calculating the influence of Reynolds number and roughness on the propeller characteristics. The main reason is that the influence of the undercritical sections on the lift-angle curve of the equivalent profile cannot be eliminated for fundamental reason, whether or not the polar curve of the undercritical sections are known. Assuming the polar curves of these sections known, a method of calculating the overcritical propeller characteristics from an undercritical test is conceivable considering the variations of the thrust and torque elements at any radius due to variations of the lift and drag coefficients and integrating over the former variations. From a practical point of view, this method does not lead further than the method of the equivalent profile because of the lack of knowledge of the polar curves of rotating undercritical sections. With overcritical conditions in the original state of the propeller, the method is useful when considering the influence of a noncontinuous roughness at the blades for which problem this method is more convenient than the process of correcting the drag-angle curve of the equivalent profile.

To outline the method, we start with the variation of the thrust coefficient and write from (3):

$$\frac{dk_T}{dx} = \frac{\pi^2}{4} z \cos^2(\beta_i - \beta) \frac{1}{D} c_L (x^2 + \lambda^2) \cos\left(\beta_i + \frac{c_D}{c_L}\right)$$

$$= \left[\frac{\pi^2}{4} z \cos^2(\beta_i - \beta)\right] \frac{1}{D} F(x, \lambda, c_L, c_D, \beta_i)$$

With variations of $c_L$ and $c_D$ at fixed values of x and $\lambda$, variations of $\beta_i$ occur, hence, the variation of $\frac{dk_T}{dx}$ at a certain radius amounts to

$$\Delta\left(\frac{dk_T}{dx}\right) = \left[\frac{\pi^2}{4} z \cos^2(\beta_i - \beta)\right] \frac{1}{D}\left(\frac{\partial F}{\partial c_L} \Delta c_L + \frac{\partial F}{\partial c_D} \Delta c_D + \frac{\partial F}{\partial \beta_i} \Delta \beta_i\right)$$

considering the quantity $\cos(\beta_i - \beta)$ independent of the small variations of $\beta_i$. Considering $\cos(\beta_i - \beta)$ also independent of x it follows that:

$$\Delta k_T = \int_{x_n}^{1} \Delta\left(\frac{dk_T}{dx}\right) dx = \frac{\pi^2}{4} z \cos^2(\beta_i - \beta) \int_{x_n}^{1} \frac{1}{D}\left(\frac{\partial F}{\partial c_L} \Delta c_L + \frac{\partial F}{\partial c_D} \Delta c_D + \frac{\partial F}{\partial \beta_i} \Delta \beta_i\right) dx$$

Calculating the derivatives we obtain:

$$\Delta k_T = \int_{x_n}^{1} \frac{\Delta c_L}{c_L}\left(\frac{dk_T}{dx} + \frac{2}{x} \frac{c_D}{c_L} \frac{dk_Q}{dx}\right) dx - 2 \int_{x_n}^{1} \frac{\Delta c_D}{c_D} \frac{c_D}{c_L} \frac{1}{x} \frac{dk_Q}{dx} dx$$

$$- 2 \int_{x_n}^{1} \frac{\Delta \beta_i}{x} \frac{dk_Q}{dx} dx$$

The lift-coefficient is assumed to depend on the angle of incidence, Reynolds number and relative roughness:

$$c_L = c_L\left(\alpha, R, \frac{k_s}{l}\right)$$

therefore

$$\Delta c_L = \frac{\partial c_L}{\partial \alpha} \Delta \alpha + \frac{\partial c_L}{\partial R} \Delta R + \frac{\partial c_L}{\partial\left(\frac{k_s}{l}\right)} \Delta\left(\frac{k_s}{l}\right)$$

From Fig. 1, the relation follows:

$$\alpha + \beta_i = \psi = \tan^{-1}\left(\frac{1}{\pi x} \frac{P}{D}\right)$$

hence, for a propeller with fixed blades:

$$\Delta \beta_i = -\Delta \alpha$$

Introducing the expressions for $\Delta c_L$ and $\Delta \beta_1$ into the relation for $\Delta k_T$, it follows that

$$(22)\quad \begin{cases} \Delta k_T = \int_{x_n}^{1} \Delta\alpha \left[\frac{\partial c_L}{\partial \alpha}\ \frac{1}{c_L} F_T + \frac{2}{x}\ \frac{dk_Q}{dx}\right] dx + \int_{x_n}^{1} \Delta R \frac{\partial c_L}{\partial R}\ \frac{1}{c_L} F_T\, dx \\ \quad + \int_{x_n}^{1} \Delta \left(\frac{k_s}{l}\right) \frac{\partial c_L}{\partial \left(\frac{k_s}{l}\right)} \frac{1}{c_L}\ F_T\, dx - \int_{x_n}^{1} \frac{\Delta c_D}{c_D}\ \frac{c_D}{c_L}\ \frac{2}{x}\ \frac{dk_Q}{dx}\, dx \\ F_T = \frac{dk_T}{dx} + \frac{2}{x}\ \frac{c_D}{c_L}\ \frac{dk_Q}{dx} \end{cases}$$

In an analogous way, we obtain the variation $\Delta k_Q$ from (4):

$$\frac{dk_Q}{dx} = \left[\frac{\pi^2}{8}\ z \cos^2(\beta_1 - \beta)\right] \frac{1}{D} c_L (x^2 + \lambda^2) \sin\left(\beta_1 + \frac{c_D}{c_L}\right)$$

to

$$(23)\quad \begin{cases} \Delta k_Q = \int_{x_n}^{1} \Delta\alpha \left[\frac{\partial c_L}{\partial \alpha}\ \frac{1}{c_L} F_Q - \frac{x}{2}\ \frac{dk_T}{dx}\right] dx + \int_{x_n}^{1} \Delta R \frac{\partial c_L}{\partial R}\ \frac{1}{c_L} F_Q\, dx \\ \quad + \int_{x_n}^{1} \Delta \left(\frac{k_s}{l}\right) \frac{\partial c_L}{\partial \left(\frac{k_s}{l}\right)} \frac{1}{c_L} F_Q\, dx + \int_{x_n}^{1} \frac{\Delta c_D}{c_D}\ \frac{c_D}{c_L}\ \frac{x}{2}\ \frac{dk_T}{dx}\, dx \\ F_Q = \frac{dk_Q}{dx} - \frac{x}{2}\ \frac{c_D}{c_L}\ \frac{dk_T}{dx} \end{cases}$$

From (22) and (23), $\Delta\alpha$ can be eliminated when referring to (2) which equation, with $\tan(\beta_1 - \beta) \doteqdot (\beta_1 - \beta)$ is written as:

$$c_L = \frac{4\pi}{z}\ \frac{D}{l}\, x \kappa (\beta_1 - \beta) \sin\beta_1$$

Since $\kappa$, at a certain radius x, depends on $\lambda_1$ we obtain:

$$\Delta c_L = c_L \left(\frac{1}{\kappa}\ \frac{\partial \kappa}{\partial \lambda_1}\ \frac{\partial \lambda_1}{\partial \beta_1} + \frac{1}{\tan\beta_1} + \frac{1}{(\beta_1 - \beta)}\right) \Delta\beta_1$$

which relation, when equated to the above expression for $\Delta c_L$ leads to:

$$(24)\quad \Delta\alpha = -\ \frac{\frac{\partial c_L}{\partial R}\, \Delta R + \frac{\partial c_L}{\partial \left(\frac{k_s}{l}\right)} \Delta \left(\frac{k_s}{l}\right)}{\frac{\partial c_L}{\partial \alpha} + c_L \left(\frac{1}{\kappa}\ \frac{\partial \kappa}{\partial \lambda_1}\ \frac{\partial \lambda_1}{\partial \beta_1} + \frac{1}{\tan\beta_1} + \frac{1}{(\beta_1 - \beta)}\right)}$$

Into this equation, the expressions

$$\lambda_1 = x \tan\beta_1, \frac{\partial \lambda_1}{\partial \beta_1} = \frac{x}{\cos^2\beta_1}$$

which are valid for optimum propellers, may be introduced as approximations.

Equations (22)—(24) are of a fairly general nature and hold for arbitrary distributions of $\frac{\Delta c_D}{c_D}$ in the radial direction which may be noncontinuous. We apply these equations to an overcritical case and refer to the smooth full scale propeller of the preceding chapter. We assume that a roughness which is equivalent to a sand roughness of the Nikuradse type with $k'_s = 0.001''$ spreads from the hub towards the tip of the propeller. The variations of the propeller characteristics are to be determined as a function of the radius x to which the roughness has spread.

The original state being overcritical, $\frac{\partial c_L}{\partial R} = 0$. Further we assume that the roughness is moderate such that $\frac{\partial c_L}{\partial \left(\frac{k_s}{l}\right)} = 0$. Then $\Delta \alpha = 0$ follows from (24).

With this, the equations (22) and (23) are simplified to:

$$\text{(22a)} \qquad \Delta k_T = -2 \int_{x_n}^{x} \frac{\Delta c_D}{c_L} \frac{1}{x} \frac{dk_Q}{dx} dx$$

$$\text{(23a)} \qquad \Delta k_Q = \frac{1}{2} \int_{x_n}^{x} \frac{\Delta c_D}{c_L} x \frac{dk_T}{dx} dx$$

the integrals taken from $x_n$ to x since, in this particular case, $\Delta c_D$ equals zero outside of the range $x_n$ to x.

Instead of introducing expressions (3) and (4) for $\frac{dk_T}{dx}$ and $\frac{dk_Q}{dx}$ respectively, we simplify the equations further by assuming semi-elliptic distributions (p. 63) and obtain

$$\text{(22b)} \qquad \Delta k_T = -\frac{32}{\pi} k_Q \int_{x_n}^{x} \frac{\Delta c_D}{c_L} x \sqrt{1-x^2} \, dx$$

$$\text{(23b)} \qquad \Delta k_Q = \frac{8}{\pi} k_T \int_{x_n}^{x} \frac{\Delta c_D}{c_L} x^3 \sqrt{1-x^2} \, dx$$

The variation of the drag coefficient $\Delta c_D$ is determined by (19) and (20) assuming the pressure resistance constant:

$$\Delta c_D = \Delta c_f = \left(1 + 2 \frac{d}{l}\right) \Delta c_{fP}$$

and the following table can be established for $s = 0.225$:

| x | l'' | $R_x$ | $\frac{l}{k_s}$ | $c'_{fP}$ | $c_{fP}$ | $\Delta c_{fP}$ | $\frac{d}{l}$ | $\Delta c_D$ |
|---|---|---|---|---|---|---|---|---|
| 0.2 | 37.7 | $1.94\times10^7$ | $3.77\times10^4$ | 0.0074 | 0.0058 | 0.0016 | 0.125 | 0.0020 |
| 0.3 | 43.1 | $2.66\times10^7$ | $4.31\times10^4$ | 0.0072 | 0.0053 | 0.0019 | 0.098 | 0.0023 |
| 0.4 | 48.0 | $3.53\times10^7$ | $4.80\times10^4$ | 0.0069 | 0.0049 | 0.0020 | 0.076 | 0.0023 |
| 0.5 | 51.9 | $4.50\times10^7$ | $5.19\times10^4$ | 0.0068 | 0.0048 | 0.0020 | 0.059 | 0.0022 |
| 0.6 | 54.1 | $5.42\times10^7$ | $5.41\times10^4$ | 0.0069 | 0.0046 | 0.0023 | 0.045 | 0.0025 |
| 0.7 | 54.6 | $6.23\times10^7$ | $5.46\times10^4$ | 0.0070 | 0.0045 | 0.0025 | 0.035 | 0.0027 |
| 0.8 | 51.7 | $6.64\times10^7$ | $5.17\times10^4$ | 0.0072 | 0.0045 | 0.0027 | 0.026 | 0.0028 |
| 0.9 | 43.1 | $6.16\times10^7$ | $4.31\times10^4$ | 0.0074 | 0.0045 | 0.0029 | 0.019 | 0.0030 |
| 1.0 | 0 | 0 | 0 | — | — | — | — | — |

The lift coefficient $c_L$ follows from (2). To avoid longer calculations, $\kappa$ and $\beta_i$ are taken from the optimum propeller, the latter from $\tan \beta_i = \lambda_i / x$ with $\lambda_i = 0.338$ at $s = 0.225$.

| x | $c_L$ | $\frac{\Delta c_D}{c_L}$ | $x\sqrt{1-x^2}$ |
|---|---|---|---|
| 0.2 | 0.251 | 0.0080 | 0.1960 |
| 0.3 | 0.243 | 0.0091 | 0.2862 |
| 0.4 | 0.236 | 0.0097 | 0.3666 |
| 0.5 | 0.207 | 0.0106 | 0.4330 |
| 0.6 | 0.181 | 0.0138 | 0.4800 |
| 0.7 | 0.156 | 0.0173 | 0.4999 |
| 0.8 | 0.133 | 0.0211 | 0.4800 |
| 0.9 | 0.134 | 0.0224 | 0.3923 |
| 1.0 | 0 | — | 0 |

| $x^3\sqrt{1-x^2}$ | $\frac{\Delta c_D}{c_L} x\sqrt{1-x^2}$ | $\frac{\Delta c_D}{c_L} x^3\sqrt{1-x^2}$ |
|---|---|---|
| 0.00784 | 0.00157 | 0.00006 |
| 0.02576 | 0.00260 | 0.00023 |
| 0.05866 | 0.00356 | 0.00057 |
| 0.1083 | 0.00456 | 0.00115 |
| 0.1728 | 0.00662 | 0.00239 |
| 0.2500 | 0.00865 | 0.00433 |
| 0.3072 | 0.01013 | 0.00648 |
| 0.3178 | 0.00879 | 0.00712 |
| 0 | 0 | 0 |

For the smooth full scale propeller, the following quantities have been obtained from the polar curve at $s = 0.225$:

$$k_T = 0.1534;\ k_Q = 0.0289$$

With these values and with the above tables, $\Delta k_T$ and $\Delta k_Q$ are determined from (22b) and (23b):

$$\Delta k_T = -0.294 \int_{0.2}^{x} \frac{\Delta c_D}{c_L} x\sqrt{1-x^2}\ dx$$

$$\Delta k_Q = 0.391 \int_{0.2}^{x} \frac{\Delta c_D}{c_L} x^3 \sqrt{1-x^2}\, dx$$

| x | $\int_{0.2}^{x} \frac{\Delta c_D}{c_L} x \sqrt{1-x^2}\, dx$ | $\int_{0.2}^{x} \frac{\Delta c_D}{c_L} x^3 \sqrt{1-x^2}\, dx$ | $\Delta k_T$ | $\frac{\Delta k_T}{k_T}$ % |
|---|---|---|---|---|
| 0.2 | 0. | 0. | 0. | 0. |
| 0.3 | 0.00021 | 0.00002 | —0.00006 | —0.04 |
| 0.4 | 0.00052 | 0.00006 | —0.00015 | —0.10 |
| 0.5 | 0.00092 | 0.00014 | —0.00027 | —0.18 |
| 0.6 | 0.00148 | 0.00032 | —0.00044 | —0.29 |
| 0.7 | 0.00225 | 0.00065 | —0.00066 | —0.43 |
| 0.8 | 0.00319 | 0.00120 | —0.00094 | —0.61 |
| 0.9 | 0.00413 | 0.00188 | —0.00121 | —0.79 |
| 1.0 | 0.00469 | 0.00234 | —0.00137 | —0.89 |

| x | $\Delta k_Q$ | $\frac{\Delta k_Q}{k_Q}$ % | $\frac{\Delta \eta}{\eta}$ % |
|---|---|---|---|
| 0.2 | 0. | 0. | 0. |
| 0.3 | 0.00001 | 0.04 | —0.08 |
| 0.4 | 0.00002 | 0.07 | —0.17 |
| 0.5 | 0.00006 | 0.21 | —0.39 |
| 0.6 | 0.00013 | 0.45 | —0.74 |
| 0.7 | 0.00025 | 0.87 | —1.30 |
| 0.8 | 0.00047 | 1.63 | —2.24 |
| 0.9 | 0.00074 | 2.56 | —3.35 |
| 1.0 | 0.00092 | 3.18 | —4.07 |

The efficiency as compared with the smooth full scale propeller decreases up to 4.1% with the entirely rough blade which result is reasonably close to the figure 4.5% calculated in A, c in a different way.

From the slope of the curve $\frac{\Delta \eta}{\eta}$ on a basis of x (Fig. 10), it follows that the same partial roughness is more effective near the tip than near the hub. Allowing a loss of efficiency of 0.5%, it is not necessary to polish the blades between the hub and the radius $x = 0.55$ in the case under consideration. Allowing a 1% loss the radius may be shifted to $x = 0.65$. Beyond $x = 0.65$, polishing becomes necessary to avoid greater losses.

To check the method, free running tests with a smooth and roughened model propeller, geometrically similar to that mentioned in A, b, have been carried out. The diameter of this model was $D = 7.09''$. To reproduce the roughness, carborundum sand was attached to the blades with varnish. After the test with the fully rough blades, the sand was taken off gradually so that tests with roughness from $x_n = 0.2$ to $x = 0.8$; 0.6; 0.4 and with smooth blades could be successively conducted. The average roughness of the sand was determined by calibrated meshes to be $k_s = 0.010''$. This figure is assumed as equivalent sand roughness of the Nikuradse type, both roughness being sand roughness and being fixed to

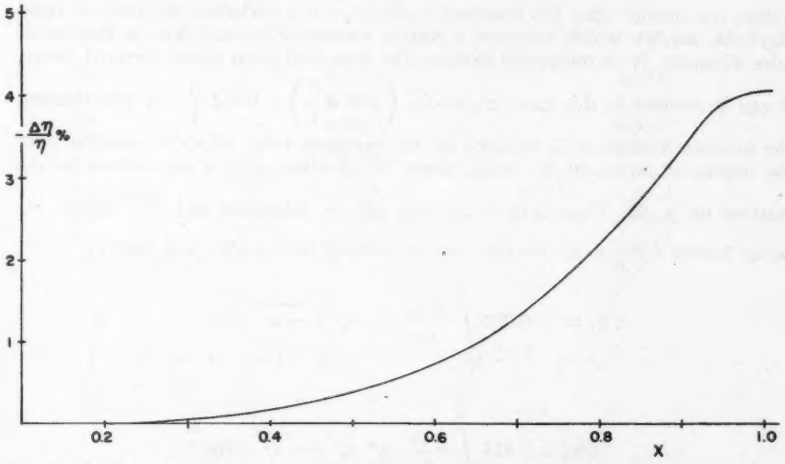


FIGURE 10.—Loss of efficiency of a partially rough full scale propeller compared with a smooth full scale propeller
Roughness from hub ($X_n = 0.2$) to X
Equivalent sand roughness $k_s = 0.001''$
$S = 0.225$

the smooth surface in the same manner. The results of the free running tests are as follows at $s = 0.225$:

| | $k_T$ | $k_Q$ | $\eta$% |
|---|---|---|---|
| (1) Blades roughened from $x_n = 0.2$ to $x = 1$: | 0.149 | 0.0378 | 53.9 |
| (2) " " " " " $x = 0.8$: | 0.151 | 0.0348 | 59.4 |
| (3) " " " " " $x = 0.6$: | 0.156 | 0.0334 | 63.9 |
| (4) " " " " " $x = 0.4$: | 0.154 | 0.0312 | 67.5 |
| (5) Blades smooth | 0.162 | 0.0326 | 68.0 |

Applying the method as developed in this chapter to these tests we have to consider that the roughness is very much exaggerated since the quantity $k_s/l$ is about 100 times greater than that of the unworked full scale bronze propeller of A,c. With such a great relative roughness, the derivatives $\frac{\partial c_L}{\partial\left(\frac{k_s}{l}\right)}$ in (22)—(24) are possibly not zero and therefore the simplified equations (22b) and (23b) may not be accurate. Only little is known about these derivatives, but they are probably small with the small lift coefficients involved, hence, they are tentatively neglected.

Further, the calculation of $\Delta c_D$ from the law of friction of a flat plate with turbulent boundary layer, which is justifiable with full scale propellers, may be inaccurate in the range of Reynolds numbers of models since the position of the transition point may be such that laminar flow of larger chordwise extent is present, particularly with smooth sections. Instead of calculating the position of the transition point [15], the values $c_D$ of the smooth sections are taken from the drag coefficients of ogivals as quoted in [3] at an equal angle of incidence. These

values are smaller than the frictional coefficients of a turbulent flat plate of equal Reynolds number which indicates a certain amount of laminar flow in the chordwise direction. With roughened sections, the transition point moves forward, hence, it can be written in this case: $c'_D = c'_{fP}\left(1 + 2\frac{d}{l}\right) + 0.012\frac{d}{l}$. In this relation, the pressure resistance is replaced by its minimum value which is possible since the angles of incidence are small, about 1°. Further, $c'_{fP}$ is determined by the relation on p. 82. Then, $\Delta c_D = c'_D - c_D$ can be calculated and $\frac{\Delta c_D}{c_L}$ follows, $c_L$ being known from p. 87. In this way we obtain from (22b) and (23b):

$$\Delta k_\Gamma = -0.332 \int_{0.2}^{x} \frac{\Delta c_D}{c_L} \; x \; \sqrt{1-x^2} \; dx$$

$$\Delta k_Q = 0.413 \int_{0.2}^{x} \frac{\Delta c_D}{c_L} \; x^3 \; \sqrt{1-x^2} \; dx$$

The expressions are evaluated in the following tables:

| x | $\frac{l}{D}$ | $l''$ | $\frac{l}{k_s}$ | $R_x$ |
|---|---|---|---|---|
| 0.2 | 0.343 | 2.432 | $2.43\times10^2$ | $2.00\times10^5$ |
| 0.3 | 0.392 | 2.779 | $2.78\times10^2$ | $2.74\times10^5$ |
| 0.4 | 0.436 | 3.091 | $3.09\times10^2$ | $3.63\times10^5$ |
| 0.5 | 0.472 | 3.346 | $3.35\times10^2$ | $4.64\times10^5$ |
| 0.6 | 0.492 | 3.488 | $3.49\times10^2$ | $5.54\times10^5$ |
| 0.7 | 0.496 | 3.517 | $3.52\times10^2$ | $6.41\times10^5$ |
| 0.8 | 0.470 | 3.332 | $3.33\times10^2$ | $6.84\times10^5$ |
| 0.9 | 0.392 | 2.779 | $2.78\times10^2$ | $6.36\times10^5$ |
| 1.0 | 0. | 0. | 0. | 0. |

| $c'_{fP}$ | $c'_D$ | $c_D$ | $\Delta c_D$ | $\frac{\Delta c_D}{c_L}$ |
|---|---|---|---|---|
| 0.0252 | 0.0330 | 0.0128 | 0.0202 | 0.0805 |
| 0.0242 | 0.0301 | 0.0120 | 0.0181 | 0.0715 |
| 0.0234 | 0.0279 | 0.0111 | 0.0168 | 0.0712 |
| 0.0228 | 0.0262 | 0.0096 | 0.0166 | 0.0802 |
| 0.0226 | 0.0251 | 0.0087 | 0.0164 | 0.0906 |
| 0.0226 | 0.0246 | 0.0082 | 0.0164 | 0.1051 |
| 0.0230 | 0.0245 | 0.0076 | 0.0169 | 0.1271 |
| 0.0242 | 0.0253 | 0.0077 | 0.0176 | 0.1313 |
| — | — | — | — | — |

| x | $\frac{\Delta c_D}{c_L} x \sqrt{1-x^2}$ | $\frac{\Delta c_D}{c_L} x^3 \sqrt{1-x^2}$ |
|---|---|---|
| 0.2 | 0.0158 | 0.0006 |
| 0.3 | 0.0205 | 0.0018 |
| 0.4 | 0.0261 | 0.0042 |
| 0.5 | 0.0347 | 0.0087 |
| 0.6 | 0.0435 | 0.0157 |
| 0.7 | 0.0525 | 0.0263 |
| 0.8 | 0.0610 | 0.0391 |
| 0.9 | 0.0515 | 0.0417 |
| 1.0 | 0. | 0. |

| | $\int_{0.2}^{x} \frac{\Delta c_D}{c_L} x \sqrt{1-x^2}\, dx$ | $\int_{0.2}^{x} \frac{\Delta c_D}{c_L} x^3 \sqrt{1-x^2}\, dx$ |
|---|---|---|
| | 0. | 0. |
| | 0.0018 | 0.0001 |
| | 0.0041 | 0.0004 |
| | 0.0072 | 0.0011 |
| | 0.0111 | 0.0023 |
| | 0.0159 | 0.0044 |
| | 0.0216 | 0.0077 |
| | 0.0272 | 0.0117 |
| | 0.0298 | 0.0138 |

| x | $\Delta k_T$ | $\frac{\Delta k_T}{k_T}$ % | Test | $\Delta k_Q$ | $\frac{\Delta k_Q}{k_Q}$ % | Test | $\frac{\Delta \eta}{\eta}$ % | Test |
|---|---|---|---|---|---|---|---|---|
| 0.2 | 0. | 0. | | 0. | 0. | | 0. | |
| 0.3 | —0.0006 | —0.4 | | 0.00005 | 0.2 | | —0.5 | |
| 0.4 | —0.0014 | —0.9 | —4.9 | 0.00018 | 0.6 | —4.3 | —1.4 | —0.7 |
| 0.5 | —0.0024 | —1.5 | | 0.00044 | 1.4 | | —2.8 | |
| 0.6 | —0.0037 | —2.3 | —3.7 | 0.00095 | 2.9 | 2.5 | —5.1 | —6.0 |
| 0.7 | —0.0053 | —3.3 | | 0.00181 | 5.6 | | —8.4 | |
| 0.8 | —0.0072 | —4.4 | —6.8 | 0.00316 | 9.7 | 6.8 | —12.9 | —12.7 |
| 0.9 | —0.0092 | —5.6 | | 0.00483 | 14.8 | | —17.7 | |
| 1.0 | —0.0099 | —6.1 | —8.0 | 0.00569 | 17.5 | 16.0 | —20.1 | —20.7 |

Comparing the calculated and measured variations of the efficiencies, the agreement is reasonable (Fig. 11). With the variations of the thrust and torque coefficient, discrepancies occur in such a direction that the calculated values of $\frac{\Delta k_T}{k_T}$ should be greater and those of $\frac{\Delta k_Q}{k_Q}$ should be smaller. This can be explained by a decrease of the lift-coefficient due to the exaggerated roughness which has not been allowed for in the numerical calculation. With decreasing lift-coefficient, both the calculated values of $\frac{\Delta k_T}{k_T}$ and $\frac{\Delta k_Q}{k_Q}$ are affected in the

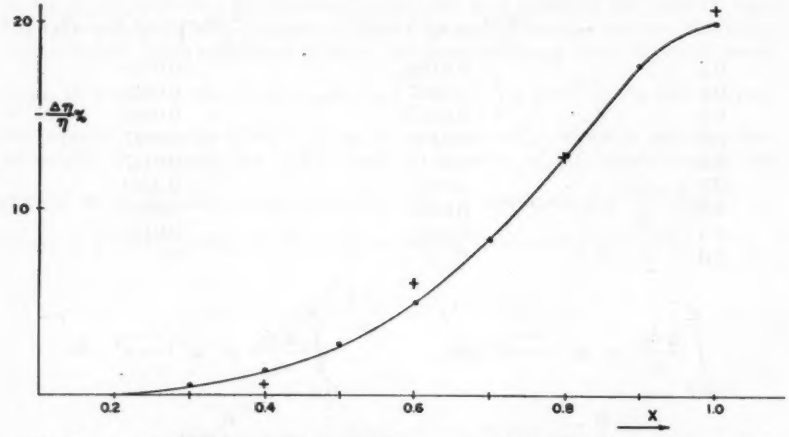


FIGURE 11.—Partially rough model propeller compared with smooth model propeller
Roughness from hub ($X_n = 0.2$) to X
Equivalent sand roughness $k_s = 0.01''$
\+ From propeller tests
—— Calculated Curve
$S = 0.225$

right direction without appreciable influence on the efficiency within the limits of $\Delta c_L$ concerned. Hence, it can be expected that the variations obtained from this method are accurate also with respect to the thrust-and torque coefficients when applied to the magnitude of relative roughness as met in practical cases.

## LIST OF MAIN SYMBOLS

| | |
|---|---|
| T | Thrust |
| Q | Torque |
| $P_o$ | Power |
| D | Diameter |
| $F_p = \pi D^2/4$ | Disc area |
| R | Tip radius |
| r | Any radius |
| $r_n$ | Hub radius |
| $x = r/R$ | Non dimensional radius |
| P | Pitch |
| z | Number of blades |
| n | Number of revolutions (per sec.) |
| $\eta$ | Efficiency |

| | |
|---|---|
| $v_o$ | Free running speed |
| $V$ | Resultant relative velocity at any section |
| $V_s$ | Ship speed (knots) |
| $\lambda = v_o/Dn\,\pi$ | Advance coefficient |
| $J = \lambda\,\pi$ | Advance coefficient |
| $s = 1 - \frac{J}{P/D}$ | Slip ratio |
| $l$ | Chord length of any section |
| $d$ | Maximum thickness of any section |
| $\alpha$ | Angle of incidence of any section |
| $k_T = T/\vartheta\, n^2\, D^4$ | Thrust coefficients |
| $c_T = T/\frac{\vartheta}{2} F_p\, v_o^2$ | Thrust coefficients |
| $k_Q = Q/\vartheta\, n^2\, D^5$ | Torque coefficient |
| $c_p = P_o \Big/ \frac{\vartheta}{2} F_p\, v_o^3$ | Power coefficient |

Suffix i: The quantity is referred to non-viscous flow

| | |
|---|---|
| $c_L = dL \Big/ \frac{\vartheta}{2}(ldr)V^2$ | Lift coefficient of any section |
| $c_D = dD \Big/ \frac{\vartheta}{2}(ldr)V^2$ | Drag coefficient of any section |
| $R = V\,l/\upsilon$ | Reynolds number of any section |
| $k_s$ | Equivalent sand roughness |
| $k_s/l$ | Relative roughness |
| $\vartheta = \varphi/g$ | Density |
| $\upsilon$ | Kinematic viscosity |

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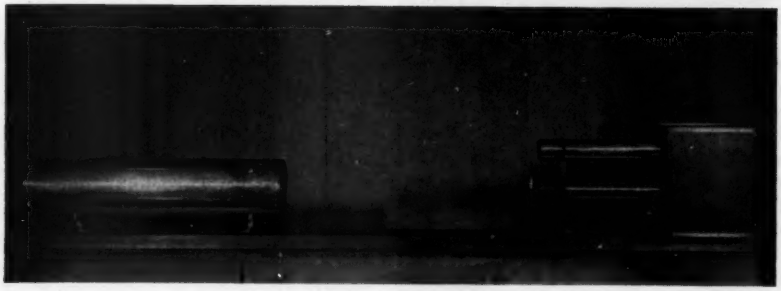


# METEOROLOGICAL RANGE METERS, MK II AND MK III

COMMANDER DAYTON R. E. BROWN, USNR

THE AUTHOR

Was commissioned in Dec. 1940 and has remained on active duty since that time, specializing in the application of optical principles to problems of search and concealment. He personally designed all of the concealment type camouflage for Naval Aircraft, submarines and landing craft used during the past war and is presently in charge of the "Visibility and Concealment Research" in the Bureau of Ships. Commander BROWN has been awarded the Bronze Star and four letters of Commendation.

This is a brief article, primarily for the layman, explaining

(A) what the MRM measures,

(B) how the unit it measures can be used, and

(C) why this type of measured unit is infinitely more useful and realistic than the so called "visibility" or "visible range" reported prior to the introduction of the MRM.

## CONTRAST REDUCTION BY HAZE

A tree covered hill close by appears very dark in strong contrast to the sky above it. The same hill appears a pale blue-gray in weak contrast to the sky when viewed at a great distance.

The difference in the apparent contrast is due to the length of the air path from the observer to the hill and the type of air in the path. In clear dry air the contrast reduction will be relatively small. On hazy or foggy days the contrast reduction will be relatively large. This is familiar to us all who have viewed distant hills or mountains day after day. Expressing this in another way we can say that on clear dry days, only a very distant hill will appear pale blue in faint contrast to the sky. On hazy or foggy days the original dark contrast may be reduced to a pale one over a relatively short distance.

Thus, if we take a definite amount of contrast reduction, say 98% from a strong contrast to a very faint one, it follows that the distance at which this particular contrast reduction takes place will depend upon the clarity of the atmosphere. The MRM measures the clarity of the atmosphere this way, namely, by specifying the distance at which any object will lose 98% of its original (or inherent) contrast. The horizontal distance, for this definite contrast reduction, is called the Meteorological Range. When the air is clear and dry the MR can be 100 miles or more. When it is hazy the MRM may read 8 miles or 12 or 13 miles or some other figure, but whatever it does read will be a definite, quantitative, description of the obscuring property of the prevailing atmosphere along a line of sight from the instrument to the horizon. The MR figure may also be regarded as an index of the contrast reduction rate per unit of distance.

At all times, even on clear days with cloudless skies, there exists some light scattering and light absorption in the atmosphere; so that so called "perfectly clear" days differ in their clarity. These differences between the obscuring properties of one "clear" day and those of another "clear day" can be measured on the MRM just as well as differences due to haze at one time and fog at another, or two different densities of haze, fog, etc. The mark II MRM is a self-contained instrument. The receiver, which must remain out of doors, is approximately 9 feet long, 4 feet high by 1 foot wide. The amplifying circuit and recorder, which may be at a remote station indoors or out, is contained in a thin metal cabinet approximately 1 × 2 × 4 feet.

Design calculations have been made for a miniaturized version of the mk II MRM suitable for use in aircraft. As yet no miniature instrument has been built. The mark II MRM as designed operates during daylight and twilight. An additional attachment is required for night operation.

The mark III MRM instrument has certain advantages when distant targets are available. It has a small 2-foot receiver mounted on a tripod and the same apparatus for amplifying and recording as the mk II. However, this instrument is not self-contained. It requires one or more black targets, preferably large black boxes open on one side, placed at known distances away from the receiver. Both MRM mk II and III measure the same quantity: MR.

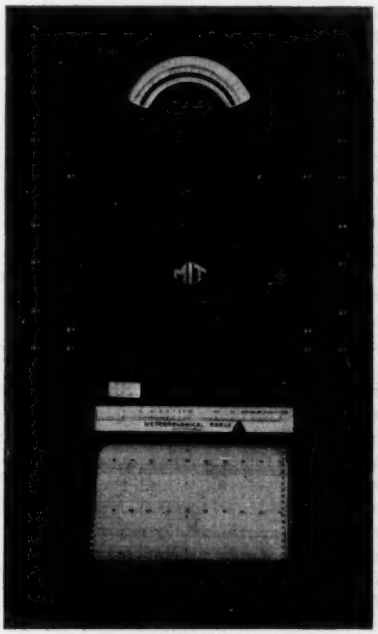
## WHY AND HOW THE METEOROLOGICAL RANGE METER WORKS

Since the light in the atmospheric path gives an increase to the apparent brightness of a dark object against the sky the meter is designed to measure this apparent brightness increase and to compare this increase with the total amount of light coming (through a path of equal size or solid angle) from the

horizon. The meter has a double optical-photoelectric-cell system. One photoelectric cell is aimed and "zeroed" on the sky near the horizon. The other system is aimed at a hole in a black tube.

Between the hole in the tube and the entrance pupil of the optical system aimed at the hole, is an air space open to the sun and sky. Within the black tube are a series of carefully spaced baffles. And at the closed end of the tube, farthest from the hole, are two black mirrors set at an angle. Thus practically *no* light from the tube is reflected or scattered back out of the hole. In other words, when viewed at zero distance, the hole is as black as it can be: actually it is somewhere around 10 times as "black" as the sky on a moonless night. ($10^{-6}$ foot candles).

Because of the "blackness" of the hole, only a very minute amount of light is required in front of the hole to raise the apparent shade. This increase is caused by the light from the sun and sky scattered in the air space between the hole and the entrance of an optical system aimed at the hole. This space light from the three-foot air path is carried through the optical system to a sensitive photoelectric cell at the exit pupil where it is transformed into an electric signal. After amplification this signal is compared to the other signal received from the light in the air path



extending from the meter to the horizon. The signal differential is relayed to a recorder and/or meter indicator scale which has been designed in accordance with the optical laws of absorption and scattering. Thus the meter reads the meteorological range in yards from 0 to 200,000.

## MILITARY USEFULNESS

There are two separate fields in which a definite measure of the MR is useful to the Armed Services: One is in describing and reporting atmospheric conditions. The other is in determining and reporting the true visibility of any given object: an airplane, tank, airstrip, or the horizon, etc.

The maximum distance to which a light gray ship may be seen differs from the distance to which a black one of the same size may be seen under the same light and haze condition. In the past, when a report was given that the so called "visibility" was eight miles, no one could tell what was visible eight miles, what six, and what could be seen at 10 miles. The eight mile estimate was based on an average of a number of observed objects of various sizes, shapes and contrasts or, in most cases at sea, on the pure guess of how close another

ship might have to come before it could be seen. Since the MR is a true measure of the contrast obscuring rate of the prevailing atmosphere, we can now for the first time, calculate how far the gray ship, the black ship or any other specific target can be seen. Likewise it is a simple matter to calculate the distance to any known target from the MR and the apparent reflectance of the target; or to calculate the inherent reflectance from the MR, the apparent reflectance and the distance to the target. In this connection attention is invited to the results of a comprehensive study on the visibility of objects initiated by the Bureau of Ships in 1942 and still in progress. This study determined the relation between the size of a target, the inherent contrast, the meteorological range and the range at which the target could be seen. These results are published in a set of nomographic charts and provide the means for calculating the visual detection range for targets of practically any size, from snorkel tips to mountains, and for all light and weather conditions which occur in nature. The charts provide means for solution of cases involving the use of any power telescope or binocular as well as for the unaided eye. In order to eliminate the necessity for having to make calculations during operations, it is planned to make calculations in advance for a number of targets of particular military importance. These will be made readily available so that as soon as the MR is measured with one of the MR meters, say aboard a carrier, reference to a chart will show just how far the pilots can see the carrier and, also how far men aboard the carrier can see the aircraft.

As studies of the optical properties of the atmosphere are advanced by the useage of these new measuring instruments practically all service problems involving visual search should become more clearly understood. For example, it will become clear what altitude is best for search for certain targets under each of a number of different haze conditions and how close together search paths should be in order to avoid blind areas and still get the greatest coverage with the fewest number of runs. Likewise it will be possible to tell pilots at what altitude and distance they can expect to see the particular landing strip or target they are approaching.

Although we have radar and sonar and "Electric Eyes," which are certainly wonderful instruments for aiding us in all manner of search problems, we are still dependent on our eyes for most of our seeing. As we learn more about the eye and its response and the physical phenomena which determine the contrasts which reach the eye, our vague doubts and guesses about what can be seen and when and how far, become clarified in a new chapter of science.

Meteorological Range Meters were invented as research instruments by Professor S. O. Duntley, a physicist at M.I.T. for work on Bureau of Ships investigations into the visibility of military targets.

# THE VORTEX TUBE

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He attended the U.S. Naval Reserve Midshipmen's School at the U.S. Naval Academy in 1943, then served as Assistant Engineer Officer of the USS *Farragut* (DD 348) and later as Engineer Officer of the USS *John R. Craig* (DD 885).

He worked as a design engineer for the General Electric Company in the Turbine-Generator Engineering Division and the Electronic Control Engineering Division in Schenectady, New York in 1946 and 1947. He was a faculty member of Syracuse University for three years and is presently a faculty member of the Department of Mechanical Engineering of the Pennsylvania State College.

Mr. COMASSAR is also the author of the article "Gas Turbine Power Plants," which appeared in the May 1949 issue of this *Journal*.

## INTRODUCTION

A vortex tube is a device having no moving parts, which is capable of separating one stream of gas into two streams, one at a higher and the other at a lower temperature than the original stream. The device is intriguing because of its extreme mechanical simplicity and the large temperature difference produced between the two discharging streams. For example,[5]* temperature differences between the two discharging streams of a specific vortex tube, operating with compressed atmospheric air as a working medium, greater than 450°F have been observed. Again, for compressed atmospheric air, vortex tubes have produced cold side temperatures as low as —58°F.

A basic vortex tube consists of a cylindrical tube with a nozzle entering the cross-section tangentially at the outer periphery, near one end of the tube length. The end away from the nozzle has either a valve or a variable annular opening near the tube's outer periphery and is known as the hot side. The end of the tube near the nozzle consists of an orifice plate with a central circular orifice. This is the cold side of the tube. In operation, the working fluid enters the tube through the nozzle, creating a vortex due to the nozzle's tangential position. A portion of this working fluid, the amount being determined by the tube design and its operating control, passes through the hot side and discharges to the surround-

* Numbers refer to references in Bibliography.

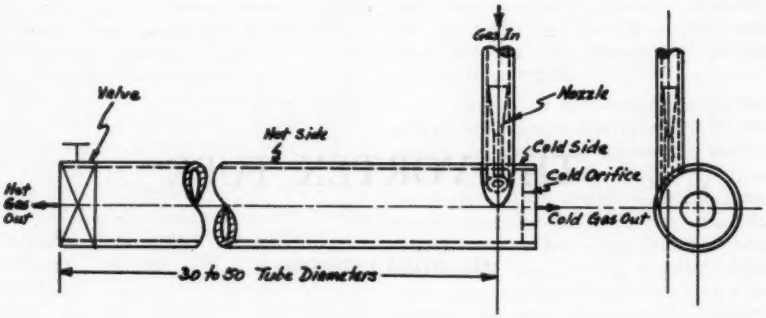



FIG. 1 - COUNTERFLOW TYPE VORTEX TUBE

ings. The remaining portion of the original entering fluid passes through the orifice of the cold side of the tube to the surroundings.

The basic vortex tube described above is of the counterflow type, an example of which is shown in Figure 1. Because of the existing flow pattern of the gas in the tube, which is described later, a parallel flow vortex tube can also be constructed. This type of tube differs from the counterflow type in that the cold orifice is located at the center of the hot side discharge cross-section and the side of the tube near the nozzle is blanked off.

The history[3, 10] of the vortex tube follows the pattern of many inventions of the past two centuries, namely that of initial interest, then skepticism and apathy and later, renewed interest. The vortex tube was invented by George Joseph Ranque, a French metallurgist and a member of the Societé Francaise de Physique, who first noticed the vortex tube effect in a centrifuge. He constructed a device to duplicate this effect and applied for patents covering it. He was granted a French Patent in 1932 and a United States Patent[12] in 1934. In the patents, Ranque gave various arrangements of the counterflow and parallel flow types of vortex tube and also gave an explanation of the phenomenon in terms of the compression and expansion of layers of fluid, which is not the commonly accepted theory of operation at this time.

Ranque realized later that his explanation was incorrect and presented a revised explanation, in 1933. This explanation agrees more closely with that of Rudolph Kassner and Eugen Knoerschild[8] and with the present day accepted theory of operation of the vortex tube, which is given later.

After the presentation of Ranque's revised explanation, skepticism of the vortex tube was expressed in the Societé Francaise de Physique, which suggested that the author and inventor was confused between static and stagnation temperatures. Ranque apparently desired to maintain secrecy concerning further developments and did not demonstrate his device to convince the skeptics. Ranque's patents were assigned to La Giration Des Fluides, Limiteé, of Montlucon, France, which was apparently a company formed by him to develop and apply his invention, and which accounted for his secrecy.

Nothing more was heard concerning the vortex tube, in Europe or the United States, until 1946, when Rudolph Hilsch of the Physikalischen Institut, Erlangen,

Germany, published a paper[6] concerning his work with the device. Hilsch had become interested in the tube after reading Ranque's paper and had performed comprehensive experimental investigation of the counterflow type of vortex tube. Hilsch's purpose was to design a tube of maximum efficiency for cooling underground mines and shafts. He did not realize this application but did succeed in using the device in a hydrogen liquefying machine. This form of the device was discovered by United States scientific teams in Germany after World War II and the associated work published by Hilsch was translated into English and circulated in the United States by an agency at Wright Field, Ohio. Hilsch's translated paper[5] was printed unabridged in *The Review of Scientific Instruments,* in February, 1947.

A relatively meager amount of information exists on the subject of the vortex tube in the scientific literature, although non-technical writers have been fairly prolific on the subject. In addition, a number of unpublished theses and papers have been written about the device. The Bibliography of this paper contains all of the sources consulted by the author and Appendix A, containing literature known to the author but not consulted, has been added to furnish a complete background to future investigators on the subject of the vortex tube.

In consulting the literature mentioned above, it has been noted that the device under consideration is variously called a "Hilsch Tube", "Ranque Tube", "Vortex Refrigerator", "T-Tube", "Separator Tube", "Ranque-Hilsch Tube", and "Vortex Tube". It is the author's contention that the latter name, "Vortex Tube", is the only appropriate one and that use of the others should be discouraged, since they refer to specific sizes and designs of the tube constructed and used for the determination of a limited amount of data. Therefore, the name "Vortex Tube" has been and shall be used in this paper to describe a device producing the effect first noted by George Ranque and investigated and popularized by Rudolph Hilsch.

Since the first publication in the United States of Hilsch's paper, a great amount of work, both on the fundamental theory and on commercial applications, has been performed. The first analytical paper on the theory was published in November 1947,[8] and dealt with the fluid mechanics involved in the flow of the working fluid through the tube. Investigation was commenced concerning applications of the tube to aircraft cooling (of cabins),[9] cooling of automobiles, liquefaction of gases, and development of a small, portable refrigerator.

Although many independent investigations were undertaken in the United States by industry and educational institutions, outside of the applications of the tube mentioned by Hilsch, to the author's knowledge the only commercial applications which have been realized are for cabin and accessory cooling in jet aircraft and in a new thermometer for measuring cloud temperatures accurately from a fast moving airplane.[11] This latter device, called a vortex thermometer, which may also be used for an aircraft speedometer, was invented by Dr. Bernard Vonnegut of the General Electric Research Laboratory in Schenectady, New York. Its principle of operation is based upon controlling the flow of air to the cold side of a vortex tube automatically, as a function of airplane speed. Cold air issuing from a vortex tube passes over a standard thermometer inserted in this air stream. The temperature of the air passing over the thermometer has been lowered by the vortex tube an amount equal to the rise in temperature experienced by the air entering the tube due to friction, which is also a function of airplane speed. The resulting reading given by the thermometer is the true

temperature of the air surrounding the airplane.

Application of the vortex tube to a gas liquefaction process, as mentioned by Hilsch, would necessitate a system such as is shown in Figure 2.

The inherent inefficiency of the tube, as pointed out by past investigators, has made it difficult to develop economically feasible applications. However, the mechanical simplicity of the device makes it attractive and further analytical and experimental investigations should lead to more varied fields for application.

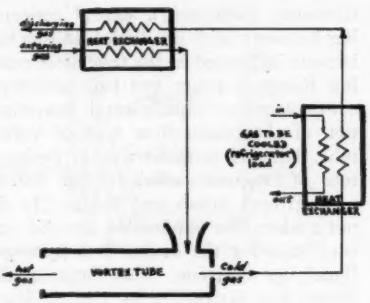



FIG. 2 – APPLICATION OF THE VORTEX TUBE TO A GAS LIQUEFACTION PROCESS

## THEORY OF OPERATION

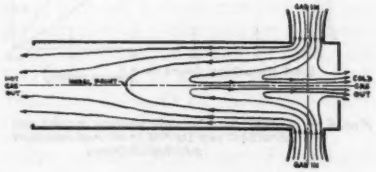
Several theories have been advanced to explain the operation of a vortex tube, but the generally accepted one at the present time is that given by Kassner and Knoernschild.[8] Writers of non-technical articles on the tube have stressed the "Maxwell's Demon" explanation, but this is obviously incorrect since the vortex tube effect is not a molecular sorting phenomenon and does not violate the Second Law of Thermodynamics.

Ranque's first explanation of the vortex tube effect, which he later retracted, assumed the two streams to be of different temperatures because of compression of the outer layers and concurrent expansion of the inner layers of the fluid in the vortex. Such a compression and expansion would result in different static temperatures of the layers but unless there was an energy transfer occurring, from the inner layers to the outer layers of the fluid, the two streams would still have the same total temperature and there would be no temperature difference after they were discharged from the vortex tube.

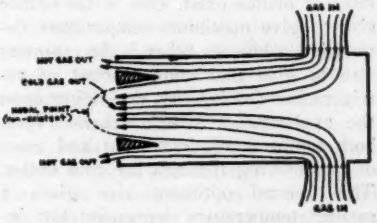
The most logical explanation of the vortex tube effect attributes the temperature difference attained to a migration of kinetic energy due to viscous shear stresses within the whirling mass of gas produced by the vortex. When the compressed gas enters the circular tube from the nozzle, the gas forms a vortex due to the nozzle's position in the tube. The vortex complies with the law of constant angular momentum, where the velocity times the radius of any particle is a constant. A radial velocity gradient therefore exists in the fluid, which has its inner layers at high tangential velocity and the outer layers at low tangential velocity. This is an example of irrotational flow. Since any viscous flow exhibits a tendency to equalize its velocity distribution, as the vortex expands axially, the irrotational character of the flow changes to rotational flow, where the normal velocity gradient disappears. In changing the velocity distribution, the higher velocity layers accelerate the lower velocity layers causing a transfer of kinetic energy outward from the tube axis. This kinetic energy transfer raises the temperature of the outer gas layers and lowers the temperature of the inner layers. However, now that a temperature difference exists in the gas, a heat transfer results, where the heat energy flows from the hot outer layers to the cold inner layers. The pressure of the

gas near the axis, where a rotational flow builds up, increases and a pressure gradient towards the cold orifice (at atmospheric pressure) exists. While the conversion of the flow continues, the innermost layers separate, and under the influence of the axial pressure gradient, proceed towards and out of the cold orifice. This separation of the layers of the gas continues until the irrotational flow is changed to a rotational one. The remaining gas, under conditions of rotational flow, progresses axially along and through the hot end of the tube. The resulting difference in temperature of the two streams of gas is due to the fact that the overall kinetic energy flux outward is greater than the heat flux inward. In addition to the velocity gradient of cylindrical layers of the gas described above, an axial velocity gradient exists between adjacent discs. Due to friction against the tube walls, downstream low velocity discs are accelerated by higher velocity upstream discs, which in turn are decelerated. Therefore, axial kinetic energy and heat energy transfers exist in the flow, contributing to the net energy interchange of gas particles. The net separation by temperature is maintained by final discharge of the two gas streams from the tube. The resulting flow pattern existing in the vortex tube is shown in Figure 3.

The vortex tube shown and referred to in the above explanation is of the counterflow type, but a parallel flow tube would be analyzed in a similar manner. The latter type of tube would necessarily have to have its cold outlet between the nodel point of the cold gas flow pattern and the nozzle. The flow pattern for this kind of tube is shown in Figure 4.



((Note: Gas is whirling while moving axially through tube))



((Note: Gas is whirling while moving axially through tube))

## DESIGN AND OPERATION DATA

Investigation of the existing literature shows that most of the work done on the vortex tube has been accomplished using atmospheric air as the working fluid in relatively small diameter (less than one inch) tubes. Some data also appears for hydrogen and carbon dioxide used separately in small diameter tubes.[7] In addition, the aspect of refrigeration and the lowest temperature available from the vortex tube have been the motivating factors in the experimental and analytical work. A brief summary of the operation, performance data and design considerations is presented here to show the extent and results of the work which has been done on the vortex tube.[2, 5, 7]

Comprehensive investigations have been made on tubes with bores varying from 0.18 inch to 0.75 inch, with corresponding values of the ratio of

total nozzle area to tube bore of 0.056 to 0.120. Results of the experiments concerned show that the higher values of this ratio are preferred and that it should be increased for tubes of larger bore. Increasing this ratio would serve to increase the capacity of a tube of given bore. Increasing the tube bore was found to give a greater maximum temperature depression, which is a corroboration of the theory of operation of the vortex tube. A larger bore would mean that the cylindrical layers of gas of highest and lowest temperature were further apart, which would serve to decrease the heat flow inward and thereby not counter effect the temperature difference obtained by kinetic energy migration as much.

One of the most important design factors is the size of cold orifice used. For a given tube bore, two optimum sizes of orifice exist. One is the orifice size to give maximum temperature depression, while the other is the optimum size to give maximum amount of refrigeration (or heating, depending upon the application), which depends upon both temperature depression and mass of gas flowing through the cold outlet. This second optimum size gives a smaller temperature depression but involves a larger flow quantity of cold gas, thereby providing a greater amount of refrigeration. Figure 5 is given to show the shape of the curves obtained with use of the two different optimum cold orifices for a particular vortex tube.

The distance between the nozzle and the cold orifice plate is another aspect which was investigated and it was found that this distance should be held to a minimum because the strongest vortex exists directly under the nozzle and a more disturbed flow results as the vortex moves away from this point. In addition, kinetic energy transfer outward takes place between adjacent radial layers of the gas in the region between the nozzle and the orifice plate. This results in a temperature difference (with

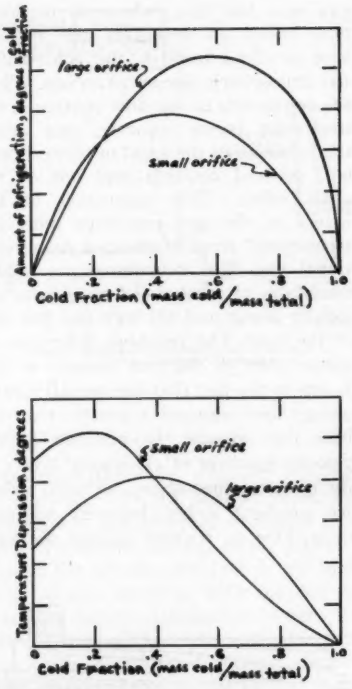



FIG. 5 — EFFECT OF OPTIMUM ORIFICE SIZES ON TEMPERATURE DEPRESSION AND MAXIMUM REFRIGERATION

the outer layers at the higher temperature) with ensuing heat transfer inward, which serves to raise the temperature of the cold gas. This is the desired vortex effect but in this particular region the outer high temperature layers are not carried into the hot gas discharge because they cannot cross the strong vortex to the hot side of the tube. Therefore, the cold gas between the nozzle and the orifice plate is raised in temperature with no beneficial effect on the overall performance of the tube.

The length of the hot tube of a vortex tube is also a factor to be considered in design. Experimental data does not fix this length definitely and results show

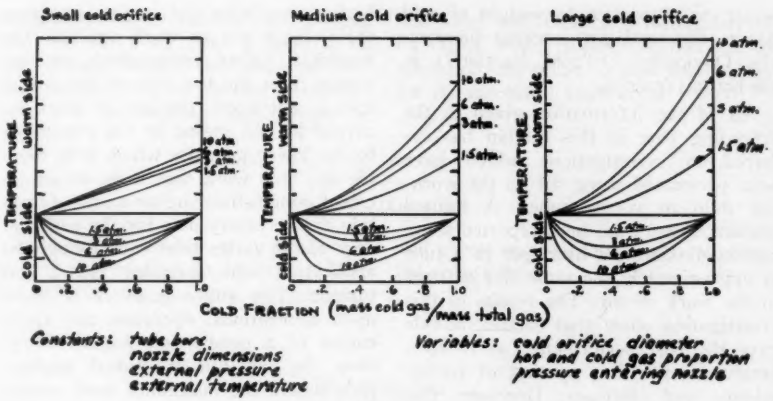



FIG. 6 – PERFORMANCE CURVES FOR A VORTEX TUBE

that this length should be from thirty to fifty tube diameters. This wide variation is not of too great importance, however, because it is determined for best performance of a tube and the difference in performance for a tube of thirty and fifty diameters in length is very small. Therefore a length of thirty tube diameters appears to be a minimum.

The number and shape of nozzles is another consideration which affects the performance of a vortex tube. Most of the experimental work reported has been accomplished using a single nozzle entering the cylindrical tube. However, multiple nozzle arrangements have been utilized in the interest of producing a more symmetrical vortex. The nozzles used in such a design were distributed evenly in the same plane around the periphery of the tube. This configuration gave improved performance over the single nozzle arrangement. It was also found that for satisfactory operation, it was essential that the nozzles used entered the tube periphery tangentially. All nozzles used were simple converging types entering a constant area section, which was added to provide smoother flow of the gas into the main tube. Converging-diverging nozzles were tried but no increase in performance was noted. However, this aspect of the investigation was not examined as thoroughly as it might have been.

In addition to these more important design considerations, several other factors were investigated and it was found that no increase in performance was obtained from vortex tubes having polished finishes for their various parts, using special materials, nor for a shape of cold orifice other than a simple disc with a central circular hole. Therefore, it is entirely satisfactory to fabricate a vortex tube from standard pipe or tubing and use a simple orifice and valve for control.

Trends of the various operating parameters are shown in the curves of Figure 6, which are drawn for a vortex tube of constant bore, constant nozzle dimensions, and constant external pressure and temperature outside the tube. The effect of varying the pressure at the nozzle, orifice diameter, and proportion of hot and cold gas flow is evident. The term "cold fraction" is used to

mean the proportion by weight of cold gas to the total gas entering the nozzle. Obviously (1-"cold fraction") is the hot gas fraction.

All of the information given in the preceding part of this section has referred to investigations which have been performed using air as the working fluid in vortex tubes. A limited amount of work has been reported using carbon dioxide and hydrogen in a tube of approximately the same size as used in the work on air. The results of this investigation show that carbon dioxide gave the best performance as to temperature depression, amount of refrigeration, and efficiency. However, this work was limited and general conclusions cannot be drawn on its basis. It is interesting to note that carbon dioxide has the lowest kinematic viscosity and the greatest density as compared to hydrogen and air.

To supplement the previously determined experimental performance data, which has just been given, the author conducted experimental work on a further aspect of the vortex tube. This aspect concerned the use of the exhaust gases of an internal combustion engine as the working fluid source for a vortex tube. The investigation was aimed at determining the highest temperature available by use of the tube rather than the lowest one, which was the objective of other investigators. The motivation in this case was the possible application of the hot gases to reheat for a gas turbine plant. The results corroborated past evidence that a high velocity of the fluid entering the tube is essential. This velocity can be obtained by a fluid at high pressure entering the nozzle of the vortex tube, but a high pressure at this point necessitates a prohibitively high back pressure for the engine supplying the exhaust gas to work against. The resultant higher temperature gas for reheat from the hot side of the vortex tube is not worth the loss of work incurred by the engine in not expanding to the lower pressure which it is capable of. This work was done on an internal combustion engine simply to obtain the necessary data for the performance of the vortex tube, even though the application was intended for a gas turbine. The above analysis is based upon conventional operation and application of a combustion engine. However, for an unconventional application, where the maximum work output of the engine is not of utmost importance, this use of the vortex tube is a decided possibility.

One further aspect of the vortex tube effect has been investigated but again, not in enough detail to justify a sound conclusion. This matter is the one of molecular separation by density of the mixture of gases passing through a tube, where the mixture is air or exhaust gases. Analysis of the gas streams issuing from the two ends of a vortex tube by means of an Orsat apparatus and a mass spectrograph have shown that no molecular separation exists. The existence of this separation is a possibility since there is a centrifuge effect in a vortex tube but the great amount of turbulence probably dissipates any separation if it is present.

The experimental determinations resulting from investigations on the vortex tube have been presented above in a general manner to show the extent of the problems involved and some of the answers obtained. More detailed results may be found in the sources referred to in the Bibliography.

## CONCLUSION

The vortex tube is a relatively new device, having been invented in 1932 and re-discovered in 1945. Its theory of operation has been satisfactorily explained and has received general acceptance. However, since it is still

young, the vortex tube at the present time has no more than a handful of applications. Because the tube is so simple mechanically, its further consideration for engineering applications is desirable, and further investigation of its effect under different conditions of operation may point out new possibilities for its successful application.

## Acknowledgment

The author wishes to express his sincere appreciation to Professor Bart J. Conta for his guidance, suggestions, and encouragement during this work on the vortex tube.

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# NEW NAVAL INDUSTRIAL ENGINEERING ORGANIZATION

COMMANDER R. E. W. HARRISON, USNR

THE AUTHOR

was born in Manchester, England in 1893. Educated at the Manchester College of Technology. Served in World War I in the Royal Engineers and saw service in Egypt, Gallipoli, Sinai, France and Belgium. As an industrial engineer designed and supervised the building of the precision grinding machinery manufacturing plant of the Churchill Machine Tool Company of England, prior to citizenship in the United States. In 1926 Director of Engineering, Cincinnati Grinders, Cincinnati Milling Machine Company. In early '34 appointed Chief of the Machinery Division of the U.S. Department of Commerce. In late 1935 became Vice President, Chambersburg Engineering Company. Transferred in 1935 from Specialist Engineering Branch U.S. Army Ordnance to Lieut. Commander in U.S. Navy as Production Engineering Specialist. Was assigned to active duty as Machine Tool Procurement Officer in the Assistant Secretary's office July 1940 and served in this capacity for two years. Subsequent duties included Special Assistant to the Under-Secretary, operation of the seized Norden Bombsight Plant at Elmira, and the Howarth Marine Thrust Bearing Plant, Philadelphia, operating in both cases as Deputy Officer in Charge for Chiefs, Bureau of Ships and Bureau of Ordnance. Commander HARRISON is a Fellow of the American Society of Mechanical Engineers, and the Royal Society of Arts—also a full member of all other leading engineering societies in U.S.A. and Europe. At present on duty in the Navy Department as Industrial Engineering Officer in the Field Activities Division of the Bureau of Ships.

The United States Navy takes particular pride in the fact that in regard to its men and materials it is never static. The foregoing is particularly true at this time in respect to the Navy's Industrial Organization which is again under critical internal review in regard to its productivity.

As actual and probable demands on the men and the ships of the fleet change to meet the changing needs of all anticipatable peace and war assignments, so the industrial organization must change promptly to meet these new requirements.

Impetus is added in the present case by the existence of Congressional endorsement requiring the institution of more detailed work control which in turn is designed to provide more adequate budgetary basis for the funds which are requested wherewith to support these productive operations.

An interesting development now under way is the creation of an Industrial Engineering Division under the Admiral in charge of field activities. This division having been assigned the mission of systematically exploring production operations at all Naval Shipyards

shop by shop with a view to placing at the disposal of shipyard Commanders the latest information regarding manufacturing techniques which have proved profitable in private industry.

The particular shops where it is believed that varying degrees of material advantage can be gained by the Industrial Engineering review process are as follows:

| *Shop No.* | *Name* |
|---|---|
| 06 | Central Tool Shop |
| 11 | Shipfitters Shop |
| 17 | Sheetmetal Shop |
| 23 | Forge Shop |
| 26 | Welding Shop |
| 27 | Galvanizing Plant |
| 28 | Plating Shop |
| 31 | Inside Machine Shop |
| 37 | Electrical Mfg. Shop |
| 38 | Outside Machine Shop |
| 41 | Boiler Shop |
| 56 | Pipe and Copper Shop |
| 61 | Shipwright Shop |
| 63 | Joiner Shop |
| 64 | Woodworking Shop |
| 81 | Foundry |
| 94 | Pattern Shop |

While it is a fact that on the payrolls of the civilian employees of the Navy Department there are expert mechanics and tradesmen long versed in the skills of their crafts, it is also realized that private industry which survives as a result of its ability to compete commercially has a continuing contribution to make which can provide that same highly competitive productivity available in a government establishment.

The present plan is to employ a trade specialist highly trained in the most up-to-date practices applicable to each of the shops listed above, and each of these men at the head of a sub-section located with headquarters in the Navy Department will be required to make a study and a subsequent constructive action report, the framework of which will be approximately as shown in the following tabulation:

EXPLORATION OR SURVEY WILL COVER

1. How job orders (paper) are received and handled.
2. How material is procured.
3. How a working schedule is established.
4. The production technique now used.
5. The mechanical equipment now used.
6. The method of assembly into a ship structure.
7. Inspection practices.
8. The (rate of production) standards now used.
9. The quality of work standards required.
10. Present sources of delays in production.
11. What recommendations are in order regarding modernization of equipment—improved machine tool specifications—costs of replacements—work handling and work transportation facilities.
12. An evaluation of each shop's contribution to the overall productive efficiency of the Shipyard.
13. An evaluation of the effect of the recommended improvements in terms of:
    (a) Reduction (if any) in man hours necessary to accommodate an agreed-on work load. Conversely what per cent of extra work could be produced with the same man-hours of labor.
    (b) Improvement in quality of work produced (1) Accuracy, (2) Finish, (3) Durability, (4) Adaptability.
    (c) Reduction in required floor space.
    (d) Improved safety of operation.

Items (11), (12), and (13) in the above tabulation form the principal elements around which the reports will center. Obviously, good mechanics should have good tools to work with, and their procurement when need is proven is a necessary first step. Adequate buildings well lighted and conveniently located are a logical next step in the scrutiny. Work transportation, by crane, by lift truck, comes next and must be backed by systematic storage and prompt safe movement, in between productive steps, and finally—equally prompt movement through inspection on to the assembly floor. Final inspection and testing of the manufactured or repaired unit—call when completed for movement to the pier where the unit can be either stored until the repair force can install it in the ship—or it can be lifted aboard and turned over to the appropriate work crew for installation. Planning the avoidance of delays in transit, is equally important, as saving time in fabrication.

Essentially what the Navy proposes to do is to improve its work's management in all of its shipyards. To bring men and machines completely up-to-date not only placing them in position to meet the current work load, but to meet any emergency which might be created by a hostile act on the part of a potential enemy.

In recruiting its specialist man power for the accomplishment of the task described above, the department has laid down the following minimum specifications:

(1) The specialist will have a comprehensive knowledge of thoroughly modern practices pertaining to shipyard work.

(2) At least ten years of experience as a supervisor in a shop or shops of a successful private manufacturer.

(3) Educational attainments sufficient to permit him to write a concise clear and complete report on practices observed by him.

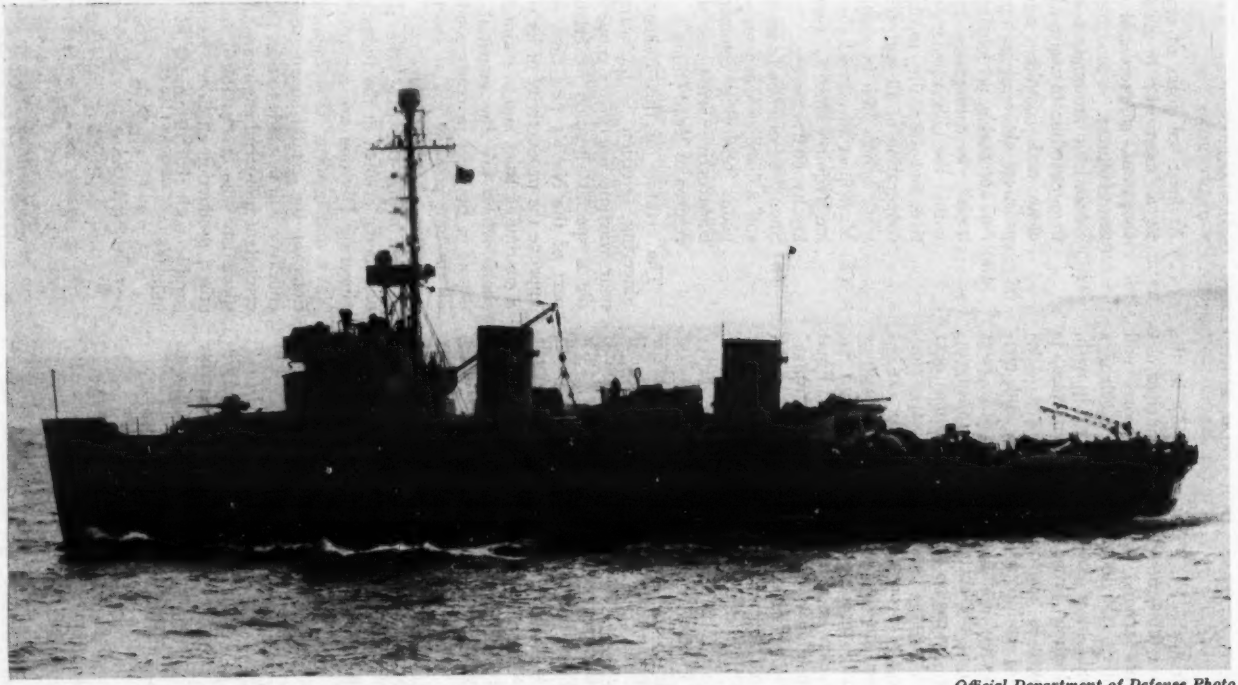
(4) An acceptable personality, good health, a willingness to travel within the U.S.A., energy, initiative, and the ability to obtain the cooperation of all with whom his work brings him in contact.

(5) Must meet all normal Civil Service requirements as regards to loyalty, character, etc.

(6) Should be essentially an observer and a listener when on visits to plants reserving comments and constructive criticisms until he returns to Head Office.

The creation of this Industrial Engineering Division is no wartime or near wartime emergency move to handle a special situation or crisis. It is part of the Navy's long-time effort to improve the productivity of its shops on a continuing basis and to maintain these shops which are the essential service depots of the fleet in ready condition to do the best possible job at short notice no matter what the future may hold.

Such being the case, the positions now being created in the Industrial Engineering Division are regarded by top Navy management as permanent positions in the establishment, and every endeavor will be made to man them with competent industrial engineers and trade specialists who can establish and maintain a production efficiency record comparable with that demanded by private industry.



*Official Department of Defense Photo*

A United States Mine Sweeper

# RECENT DEVELOPMENTS IN IMPROVING THE MARINE BORER RESISTANCE OF LUMBER AND PLYWOOD USED IN PLANKING NAVAL VESSELS

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THE AUTHOR

Received his B.S. in Chemistry, University of Pittsburgh, 1933. He is a member of the American Chemical Society. He worked in chemical warfare development (gases and gas masks) until 1937. Then he became a metallurgical inspector in a steel mill until 1940. He was appointed as civilian chemist at the Industrial Test Laboratory of the Philadelphia Naval Shipyard in 1940, where he has spent two years on chemical inspection of non-ferrous alloys and eight years in application developments in wood preservatives, wood, and life floats.

*Studies of a number of toxic impregnants, sheathing materials, and surface coatings conducted for the Navy during the past seven years; a brief historical review of protective methods is included.*

Men have been sailing the seas since our earliest written records, and until about the last century their sailing was done on wooden bottoms. Even today, most of our smaller craft are built of wood—whether commercial or pleasure craft, or the smaller Naval vessels. For just as long, the mariners have been plagued with the twin problems of keeping one group of marine organisms (marine borers) from weakening the bottom planks by tunneling through the wood and another group from growing in such masses on the bottom surface (fouling) that progress through the water was seriously hampered. Many of the protective methods tried in the past were intended to solve both problems, some with fair success for at least a limited time. Any treatment of bottom planking for protection against borers should either have some antifouling value in itself or at least, should not interfere with subsequent application of an antifouling coating. Aside from such interference, however, the present studies concern mainly methods of protection against the boring animals.



A United States Mine Sweeper

## NATURE OF THE MARINE BORERS

The principal wood-boring marine organisms are the shipworms, pholads, and Limnoria. Of these, the shipworms are responsible for most damage to wooden vessels in operation, although pholads and Limnoria also could cause considerable damage to unprotected vessels tied up for long periods in infested waters.

The common name, shipworms, is applied to two genera of bivalve mollusks, Teredo and Bankia, each of which includes numerous species, all very similar in many respects. All bore into wood in about the same manner and are apparently affected similarly by wood preservatives (with some exceptions). The young (larval) shipworms develop from eggs fertilized, in some species, after ejection into the water, and in other species, within the parent, where they are held in the gills until the larvae are fully developed. The maximum duration of the free-swimming larval stage has been estimated at from two to four weeks, during which time the animal resembles other bivalve larvae. The larvae, now perhaps ¼-millimeter in length, which lodge on suitable wooden surfaces develop into a new form and begin to burrow into the wood. The body elongates into a worm-like shape of which only the head is covered by the hinged shells, which now constitute the boring tool, edged with rows of microscopic teeth. The tail part is firmly attached to the wall of the tunnel near the entrance. The shells and body grow rapidly in diameter (to ½ inch or more in some species) as the tunnel is made longer; shipworms have been reported four feet or more in length, and one- to two-foot specimens were frequently found in the present studies. The entrance hole is not increased much in size, so that the animal is imprisoned in its tunnel, which is partially lined with a deposit of lime. Two fleshy siphons at the tail end, for intake and expulsion of water, may be extended as much as an inch from the entrance or the hole may be plugged at will with two calcareous tail members (pallets). The animal may thus seal the tunnel and withstand for some time unfavorable external conditions such as removal to fresh water or into the air. Shipworm tunnels are frequently found in unprotected wood in such numbers that only a web of wood remains, yet the tiny entrance holes in the surface may be visible only on close inspection. Shipworms of one or more species are found in most coastal waters and salt-water harbors around the world, although extreme dilution with fresh water or pollution with industrial wastes, acids, oils, etc., may render some ports relatively safe for wooden vessels. In colder waters, the breeding and growing seasons are usually rather short, whereas in the tropics, breeding and attack on exposed wood are more or less continuous throughout the year and the need for protective measures correspondingly greater.

The pholads are a related family of bivalve borers, of which two genera, Martesia and Hiata, have been found in some numbers in wooden structures. They resemble small, fat clams in general appearance and, unlike the shipworms, are completely contained in their hinged shells and do not burrow into wood to a depth much greater than the length of the shell, which is usually not over an inch. The pholads make somewhat larger entrance holes, but grow still larger as they burrow, so that they too are imprisoned in their tunnels. Pholads are found around the world but are less prevalent than shipworms and Limnoria, and are responsible for much less damage, even though their attack is more difficult to prevent. Wood impregnated heavily with creosote or other preservatives or with synthetic resins was frequently found damaged by

pholads although practically untouched by shipworms.

Limnoria are smaller animals, crustaceans, about one-eighth inch long, whose burrows are confined mainly to the surface of the wood or at most to about one-half inch in depth. They are free to move about on the wooden surfaces but usually burrow in just one place. In large numbers, they rapidly reduce the surface to a network of burrows, easily eroded by motion of the water, after which the burrows may be extended deeper into the wood. Examples of their damage are numerous along the coasts, as piling and bulkhead timbers eaten entirely through at the intertidal level. Examples of untreated piling have been reported destroyed within a year by Limnoria. Even heavily-creosoted wood is not immune to attack by Limnoria, and has been reported as occasionally suffering severe damage by this organism.

## RECENT AND PAST PROTECTIVE METHODS

Modern antifouling paints, applied at regular intervals to the bottoms of most wooden craft, not only prevent most fouling but are also effective in preventing the entrance of borers into the wood so long as the paint film remains intact. In the absence of any completely suitable, more permanent protection, recent general practice has been to apply generous layers of antifouling paint and to repaint after very short intervals when the vessels operate in borer-infested waters. Frequent repainting is costly, however, and almost impossible in combat areas. Thus there still remains the problem of providing some more permanent protection for the wooden bottoms which will remain after the paint has lost its adherence on aging or has been scraped off mechanically in undocking or in beaching the vessels or by contact with floating debris.

An excellent summary of protective methods used in the past against shipworms is found in a recent report on the prevention of marine fouling.[1] Literally hundreds of materials have been suggested and tried on wooden bottoms, including many apparently ridiculous materials of a noxious nature. Among the materials more or less widely used prior to the eighteenth century were animal hides, sheet lead, and pitch or tar or asphalt either alone or in mixtures with hair, tallow, oil, or resin. An outer sheathing of wood was sometimes applied, to be sacrificed to the shipworms and ripped off and replaced before the heavier inner planking became riddled. Some records mention charring of the wood surface as a protective measure. All those measures had serious disadvantages and most were ineffective for more than short periods. Then, in the eighteenth century, the British Navy made what was apparently the first trial of sheet copper nailed over the ship's bottom (a frigate, H.M.S. *Alarm)* to prevent the entrance of borers. The trial was very successful and the copper was discovered effective also in preventing the attachment of fouling organisms. Copper sheathing was far better than any of the older materials but shipbottom problems were not entirely solved. The copper is not permanently antifouling; its antifouling properties are lost during contact with iron or other metal fastenings; its rate of wear (or solution in sea water) is appreciable; it promotes corrosion of iron or other metal nearby; it is soft and easily punctured and torn loose from its fastenings. Despite these shortcomings, sheet copper is still used to protect many wooden bottoms in waters heavily infested with borers.

For at least the last several centuries and probably earlier among the natives who had such woods available for boat

lumber, a few tropical woods have been recognized as highly resistant to penetration by shipworms. One report has been noted of an old Australian penal ship built of teak which was still sound and seaworthy after a century afloat. There are a few other tropical woods which have records of excellent service in borer-infested waters; Greenheart and manbarklak from South America, turpentine wood from Australia, and possibly a few others. All of these are hard, heavy woods most of which have a high content of hard, granular silica distributed throughout the wood cells. It is the abrasive action of the hard particles of silica which is thought to deter the drilling of shipworms—as it also provides an excellent wearing surface in teak decking—but it also dulls the edges of saws and other cutting tools at an extremely high rate. The weight, difficulty of working, and remoteness of the sources of these tropical woods have undoubtedly kept their use in ships and boats to a minimum. Teak is imported in some quantity but is used mainly for weather decking.

For just about a century, the impregnation of wood with various liquid preservatives under pressure has been practiced in this country. And the value of coal tar creosote against shipworms has been known for some time. One early provincial patent (S. Carolina) was issued in 1716 to cover a spirit of tar (which may have been very similar to our present creosote) advocated to protect ship planking against shipworms and decay. But few records are available of any extensive use of creosote-treated ship planking, other than on barges, floating drydocks, and other relatively un-mobile structures. Coal-tar creosote (impregnated under pressure) became the standard preservative for marine piling but several undesirable properties have undoubtedly limited its use in wooden craft generally: Objectionable odor and appearance, doubtful paintability, and the added weight of the necessarily heavy treatments. However, wooden parts other than planking of some few World War I vessels were treated with creosote, probably by brushing or swabbing, to protect against decay. In World War II, a few large wooden vessels were given an outer sheathing of pressure-creosoted lumber. No definite records were available on the service suitability of the treated sheathing.

During the early war activity in tropical waters, then, there was no completely adequate protection available against marine borer attack on wood vessels, and no recommendations for any preservatives other than creosote which could be applied to wooden planking to protect it for a few months after failure of the paint coating. Most commonly recommended were frequent repainting with toxic paints or sheathing with thin sheet copper below the waterline. Frequent beaching of small boats to expose the bottoms to air for a few days and anchoring larger wooden craft in fresh or only slightly brackish water for a week or two were also recommended to kill any borers already in the wood. Vessels so treated are of course subject to renewed attack on their return to salt water. Wooden vessels far at sea are of course not subject to fresh attack by the borers, since the range of the larval form which settles on the wood is limited to the immediate vicinity of the breeding adults, in the timber structures, driftwood, and tree roots in the coastal waters.

Necessarily vague reports from tropical areas early in the war indicated that the service life of some types of unsheathed wooden vessels was limited to a few months due to damage caused by marine borers. On other vessels, thin metallic sheathing had been reported to have suffered considerable damage (and immediate loss of effectiveness against the borers) by scraping over coral rock —annual replacement was estimated as high as fifty percent of the sheathing.

Toxic bottom paints, normally effective against the borers, were either unavailable or were not as effective or durable as the paints available in this country. Exposure of the bottom to air or fresh water would be of only temporary benefit and would probably prove impracticable in the stress of war activities. It was considered, accordingly, that discovery of a suitable penetrating preservative, which would increase the safe life of such wooden vessels by even a few months would be of considerable practical benefit to the Navy. Also to be considered were other methods of protection, including the use of various sheathing materials or modifications of the planking materials, since it was unlikely that any one method of protection would be suitable for all types of wooden vessels.

## EXPOSURE OF PRESERVATIVES AND SHEATHING MATERIALS TO BORER ATTACK

The liquid preservatives to be tested were injected into wooden panels, ¾ by 3 by 18-inches in size, for exposure in borer-infested waters. Most of the sheathing materials tested were tacked around pine sapwood panels of the same size; when all sides of the wood could not be covered, the exposed edges were protected by several heavy coats of toxic antifouling paint. Some of the thicker materials such as the laminated woods, were cut into panels of about the same size and mounted alone on the exposure racks.

The treated wooden panels were bolted onto six-foot flat iron bars for shipment to the exposure stations and subsequent immersion in the sea water, several feet below low-tide level. Twenty pairs of panels, bolted back to back through the bar, were mounted on each bar, and each bar included one or more untreated panels as an indicator of the intensity of borer attack. Typical racks of panels after exposure are shown in Figure 1. Four different exposure stations were used; the two most satisfactory and convenient proved to be those at Kure's Beach, N. C. (maintained by the International Nickel Company in cooperation with Ethyl Dow Company) and at Daytona Beach, Fla. (a commercial testing station). Most of the later exposures were made at those two stations; consistently, during the active borer season (from about May to December), untreated wooden control pieces were completely destroyed by borers within two or three months. Another complete set of panels of the first exposure series was exposed to borer attack at Almirante, Panama, through the cooperation of the Wm. F. Clapp Laboratories and the United Fruit Company. Extremely heavy borer attack was found there, almost continuous throughout the year; but shipping to and from this station during the war was too difficult and no further exposures were made there. Another station at Manaimo, British Columbia, (a biological station of the Canadian Bureau of Fisheries) also was tried for one series of exposures. Borer attack there was much less severe and so proved to be a poorer test of the protective measures.

For each exposure series, a sufficient number of replicate panels of each treatment were provided to permit withdrawal of complete sets of panels at a number of intervals during the exposure. Thus, it was possible not only to examine the surface damage, but also to split open the panels for more thorough examination in the laboratory. Most treatments were represented by duplicate or triplicate panels in each withdrawal group. Uniformity of the results obtained was indicated roughly also by the consistency of observations in subsequent inspections of similarly-treated panels. Figure 2 illustrates the arbitrary scale used to record the degree of borer damage to the exposed panels.

## PRESERVATIVE TREATMENTS

In the first series of preservatives tested, three methods of treatment were used: Pressure impregnation, consecutive soaking in hot and cold baths of the preservative, and a short (three minute) dipping treatment roughly comparable to treatment by thoroughly brushing or spraying. The treatments with any one preservative were found effective in the order listed, as would be expected from the weights of preservative absorbed by the wood in each method of treatment. Similarly, the preservatives were found effective in several different woods in proportion to the weight absorbed by the wood. In later exposures therefore, only pressure treatments were used, and only one wood, southern yellow pine sapwood, to evaluate the various preservatives. It appears valid to assume that the preservatives will be effective in the same general order in almost any other wood and by any other treatment method.

For the pressure treatments, a twelve-pound (per cubic foot of wood) creosote treatment was selected as the standard for comparison with other oil preservatives or solutions in petroleum solvents. For the aqueous preservatives, the first treatments (with acid cupric chromate) were made to provide approximately one pound of dry salts per cubic foot of wood. One-half pound is the minimum normally specified for this salt, which is not recommended, however, for locations where constantly wet. Concentrations of other salt preservatives were selected to give comparable absorptions, usually of the metallic ion.

For the non-pressure treatments, the same concentrations of solutions were used. A three-minute dip treatment was chosen as roughly comparable to a thorough flooding of the wood by swab, brush, or spray. For the intermediate, hot-and-cold bath treatments, duration of time in each bath was set arbitrarily at one-half hour (one hour for some few experiments) and the temperature of the hot bath as high as convenient and practical—cold bath at room temperature for convenience (at 115-125°F. for creosote, to reduce its viscosity).

All panels treated by non-pressure means were used for the exposure tests, while the pressure-treated panels were selected to obtain only those panels which had absorbed weights of preservatives in a narrow range. Thus, the variations of exposure results among individual pressure-treated panels was much less as would be expected.

## EXPOSURE TEST RESULTS

In Table 1 following are summarized the results of exposure tests of the various preservatives and of some surface coatings. All test panels reported there (other than coatings) were of southern yellow pine sapwood, impregnated by pressure treatment.

The amounts of the various toxics absorbed by the wood varied rather widely but are as nearly comparable as was practical, within the limits imposed by the solubility of the toxics, viscosity of the solutions, and the concentration of available solutions.

The exposure stations are indicated only by initials: KB for Kure's Beach, North Carolina; DB for Daytona Beach, Florida; AP for Almirante, Panama.

In section C of the table (resin impregnants), "weight of toxic" should of course be interpreted "weight of resin."

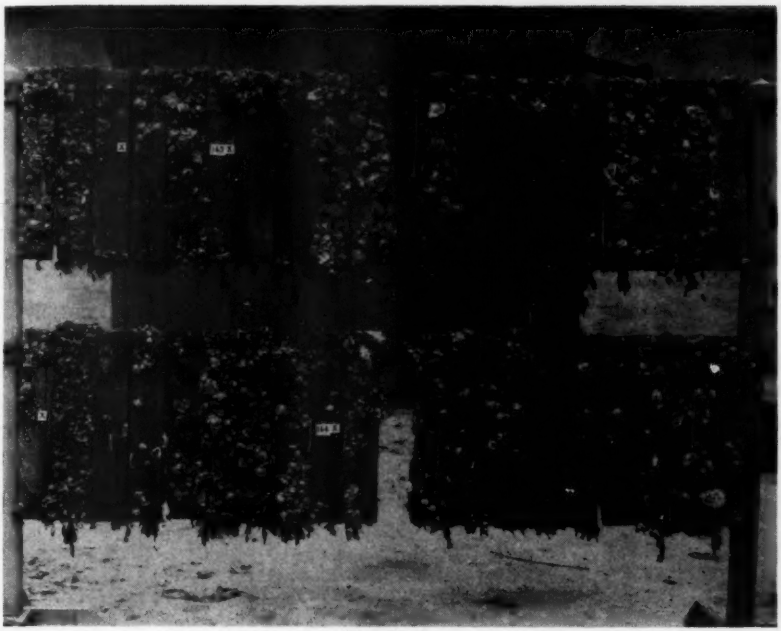

FIGURE 1.

Two six-foot racks of wooden test panels, immersed in seawater near Daytona Beach for nine months. The fouling, typical of this exposure station, consists mainly of barnacles and oysters. The cleaner panels were coated with an antifouling paint. Severe damage by borers is visible in several panels.

## CONCLUSIONS FROM EXPOSURES OF TABLE 1

1. Only two toxic impregnants approached or equalled in protection the twelve-pound creosote treatment (and the twelve-pound creosote-coal tar solution), over the relatively short exposures reported here: (a) a 2.4-pound (dry salts) treatment with acid cupric chromate, and (b) a 1.5-pound treatment with ammoniacal copper arsenate. A very similar salt treatment, with copper chromate-arsenate, exposed later, has also provided excellent protection for at least 18 months (two borer seasons). Of the protective materials examined to date, these particular salt preservatives appear the most promising for application to the planking of new wooden vessels.

2. Two of the four antifouling paints tested prevented all borer attack over the entire exposure: (a) Navy formula 16X, and (b) an NDRC formulation, AF-22. Both paints contain large amounts of cuprous oxide pigment (percentages are shown in the table).

3. Another surface protection, a resin-impregnated fiber surfacing bonded onto plywood permitted no borer penetration over the longest exposure observed, thirty months.

4. Four additional toxics provided sufficient protection in their initial short

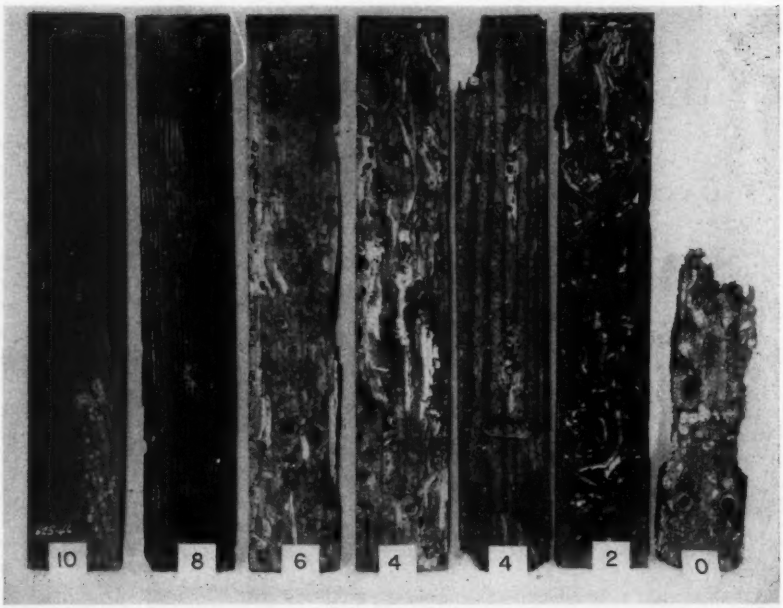


FIGURE 2.

Typical borer-damaged wood panels, illustrating the rating scale used to record the degree of damage, from 10 (no damage) to 0 (destroyed). The round openings are the pholad tunnels. The longer tunnels, many lined with lime, were made by shipworms; the thin surface of wood over the tunnels was removed here to show the tunnels more plainly.

trials to warrant further study: (a) copper sulfonate, (b) copper pentachlorphonate, (c) copper resinate, and (d) octachlordiphenoquinone.

5. Three of the synthetic resins provided protection for relatively short terms. Melamine resin, at fairly heavy concentration in the wood, protected fairly well for two borer seasons. Phenol-formaldehyde and furane resins were only slightly less effective. The use of these resins would be considered in special applications as in molded, laminated small boats, or in special underwater parts of molded construction, or in surfaced plywoods for boat planking or sheathing—rather than for the impregnation of solid wood planking.

## EXPOSURE RESULTS FOR NON-PRESSURE TREATMENTS

A few of the preservatives were applied to several different woods by the non-pressure methods described previously; some panels were coated with antifouling paint prior to exposure, some exposed unpainted.

*Hot-and-cold-bath Treatments.*

Creosote A in pine permitted only light damage by borers in 26-28 months.

Cupric chromate (3% solution) in pine permitted light to moderate damage in about 14 months.

Cupric chromate (5%) in pine permitted light damage in 18 months.

Creosote B in pine permitted light to heavy damage in 18 months.

Several different copper naphthenates

## TABLE 1

| Item No. | Toxic Used | Wt. of toxic, lbs. per cubic ft. of wood | Exposure— Date | Station | Months of exposure prior to—borer damage: Light | Moderate | Severe | Remarks |
|---|---|---|---|---|---|---|---|---|
| | *A: Toxics applied as oils or in oil or other organic solvents.* | | | | | | | |
| 1. | Coal tar creosote A | 12 | 9/43 | KB | 26 | | | Undamaged at end of test. |
| | | | 10/43 | DB | | | 28 | Mostly L. (*Limnoria*), few P. (pholads), no worms. |
| | | | 1/44 | AP | 17½ | | | Undamaged at end of test. |
| 2. | Coal tar creosote B | 12 | 5/44 | KB | 30 | | | Shipworms and *Limnoria*. |
| | | | 6/44 | DB | 17 | | | *Limnoria* and pholads. |
| | | 6 | 5/44 | KB | | | 30 | Mainly L., some pholads and worms. |
| | | | 6/44 | DB | | | 17 | Destroyed by L., some worms and pholads. |
| | | 16 | 5/44 | KB | 30 | | | Undamaged at end of test. |
| | | | 6/44 | DB | 17 | | | Pholads, some L. Test ended. |
| | | 20 | 5/44 | KB | 30 | | | Undamaged at end of test. |
| | | | 6/44 | DB | 17 | | | Pholads and L. Test ended. |
| 3. | Coal tar creosote C | 12 | 7/45 | KB | 28 | | | *Limnoria*. |
| | | | 7/45 | DB | 6 | | 30 | Destroyed by L., few pholads. |
| 4. | Creosote C and copper naphthenate (5:4 by wt.) | 5.4 (total) | 7/45 | KB | 16 | | 28 | Shipworms and *Limnoria*. |
| | | | 7/45 | DB | | | 18 | Mainly L., some pholads and worms. |
| 5. | Copper naphthenate A | 3 | 9/43 | KB | 19 | 26 | | |
| | | | 10/43 | DB | 11 | | 28 | Destroyed. |
| | | | 1/44 | AP | 17 | | | |
| 6. | Copper naphthenate B | 2 | 5/44 | KB | 15 | 18 | | |
| | | | 6/44 | DB | 5–15 | 18 | | |
| 7. | Copper naphthenates (12 different toxics from various sources) | 2–4 | 7/45 | KB | 16 | | 28 | Shipworms. |
| | | | 7/45 | DB | | | 18 | |
| 8. | Creosote—coal tar solution (4:1 by wt.) | 12 (total) | 5/44 | KB | 30 | | | Undamaged at end of test. |
| | | | 6/44 | DB | 12 | 17 | | Mainly *Limnoria*, few pholads. |
| | | 16 (total) | 5/44 | DB | | 17 | | L. and pholads, very few worms. |
| | | 20 (total) | 5/44 | DB | 17 | | | *Limnoria* and pholads. |
| 9. | Copper sulfonate | 4.6 | 7/45 | KB | 16 | | | Very slight attack. End of test. |
| | | | 7/45 | DB | 18 | | | Mainly pholads. |
| 10. | Copper pentachlorphenate | 1.3 | 7/45 | KB | 16 | | | |
| | | | 7/45 | DB | 13 | 18 | | Worms and pholads. |
| 11. | Copper resinate | 2.2 | 7/45 | KB | | | 13 | Mainly shipworms. |
| | | | 7/45 | DB | 6 | | 13 | Shipworms and *Limnoria*. |
| 12. | Octachlordiphenoquinone | 2.2 | 7/45 | KB | 13 | 16 | | Shipworms and *Limnoria*. |
| | | | 7/45 | DB | 6 | | 13 | Destroyed, mainly by L., few pholads. |
| 13. | Pyridyl mercury stearate | 1.1 | 7/45 | KB | | 4 | 13 | Shipworms. |
| | | | 7/45 | DB | 6 | | 13 | Shipworms. |
| 14. | Copper naphthenate and pyridyl mercury stearate (36:1 by wt.) | 1.6 (total) | 7/45 | KB | 4 | 16 | 28 | Destroyed by worms and *Limnoria*. |
| | | | 7/45 | DB | 6 | | 18 | Destroyed by worms, L., and pholads. |
| 15. | Copper naphthenate and phenyl mercury oleate (65:1 by wt.) | 1.6 (total) | 7/45 | KB | 4 | | 16 | Shipworms and *Limnoria*. |
| | | | 7/45 | DB | 6 | | 18 | Destroyed by worms, L., and pholads. |
| 16. | Phenyl mercury oleate | 0.06 | 9/43 | KB | 3 | | 10 | Shipworms only. |
| | | | 10/43 | DB | | | 3 | Shipworms only. |
| | | | 1/44 | AP | | | 3 | Shipworms only. |
| | | 0.12 | 7/45 | KB | | | 4 | Shipworms and few *Limnoria*. |
| | | | 7/45 | DB | | | 6 | Shipworms, *Limnoria*, and pholads. |

TABLE 1 (Continued)

| Item No. | Toxic Used | Wt. of toxic, lbs. per cubic ft. of wood | Exposure— Date | Exposure— Station | Months of exposure prior to—borer damage: Light | Moderate | Severe | Remarks |
|---|---|---|---|---|---|---|---|---|
| 17. | Pentachlorphenol and 2-chlor-o-phenylphenol (3:2 by wt.) | 0.6 (total) | 9/43 | KB | 2 | | 10 | Shipworms. |
| | | | 10/43 | DB | | | 3 | Shipworms. |
| | | | 1/44 | AP | | | 4 | Shipworms. |
| 18. | Pentachlorphenol | 1 | 7/45 | KB | 4 | 13 | 16 | Shipworms. |
| | | | 7/45 | DB | 6 | | 13 | Shipworms, *Limnoria*, and pholads. |
| 19. | Styrene dibromide | 2.1 | 7/45 | KB | 2 | 4 | 13 | Shipworms and some *Limnoria*. |
| | | | 7/45 | DB | | 6 | 13 | Destroyed by worms., L., and pholads. |
| 20. | D.D.T. (dichlordi-phenyltrichlorethane) | 3 | 7/45 | KB | | 2 | 13 | Shipworms. No *Limnoria*. |
| | | | 7/45 | DB | | 2 | 6 | Shipworms and pholads. No *Limnoria*. |
| 21. | A proprietary "clear" creosote | 3 | 7/45 | KB | | 2 | 4 | Destroyed by worms, few L., and pholads. |
| | | | 7/45 | DB | | | 2 | Destroyed by worms, L., and pholads. |
| 22. | Mercury naphthenate | 0.09 | 7/45 | KB | | | 2 | Destroyed by shipworms. |
| | | | 7/45 | DB | | | 2 | Destroyed by shipworms and pholads. |
| 23. | Mercury and zinc naphthenates (1:20) | 0.9 (total) | 7/45 | KB | | 2 | 13 | Destroyed by shipworms. |
| | | | 7/45 | DB | | | 2 | Destroyed by worms and pholads, few L. |
| 24. | Copper "phenyl" naphthenate | 2 | 7/45 | KB | 4 | | 16 | |
| | | | 7/45 | DB | 6 | | 18 | |
| 25. | s-diorthotolyl thiourea | 1.6 | 7/45 | KB | | | 2 | Destroyed by shipworms. |
| | | | 7/45 | DB | | | 2 | Destroyed by worms, L., and pholads. |
| 26. | Naphthenic acids (12 samples from various sources) | 2.4 | 7/45 | KB | | | 4 | Destroyed. |
| | | | 7/45 | DB | | | 4 | Destroyed. |
| | *B: Toxics applied in aqueous solutions.* | | | | | | | |
| 27. | Acid cupric chromate | 1.2 | 9/43 | KB | 14 | | 26 | Shipworms. |
| | | | 10/43 | DB | 13 | | 28 | Shipworms, some pholads, few L. |
| | | | 1/44 | AP | 17 | | | End of test. |
| | | 2.4 | 5/44 | KB | 30 | | | Undamaged at end of test. |
| | | | 6/44 | DB | 17 | | | Undamaged at end of test. |
| 28. | Ammoniacal copper arsenite | 1.5 | 5/44 | KB | 30 | | | Undamaged at end of test. |
| | | | 6/44 | DB | 17 | | | Worms and few pholads. End of test. |
| 29. | Silver nitrate | 0.7 | 7/45 | KB | 2 | | 13 | Destroyed by worms and many L. |
| | | | 7/45 | DB | | 6 | 13 | Destroyed by worms, L., and pholads. |
| 30. | Mercurous nitrate | 1.6 | 7/45 | KB | | 2 | 13 | Destroyed by worms. No *Limnoria*. |
| | | | 7/45 | DB | 2 | | 6 | Destroyed by worms and pholads. Few L. |
| 31. | Copper sulfide | 0.37 | 7/45 | KB | 2 | | 4 | Shipworms. |
| | | | 7/45 | DB | 2 | | 6 | Shipworms, some L. and small pholads. |
| 32. | Copper chromate-arsenate | 1.4 | 6/46 | KB | 24 | | | Undamaged at last inspection. |
| | | | 6/46 | DB | 24 | | | Undamaged at last inspection. |
| 33. | "Copperized" chromated zinc chloride | 1 | 6/46 | KB | 18–24 | | | |
| | | | 6/46 | DB | | | 14 | Shipworms and pholads. |
| 34. | "Copperized" chromated zinc chloride urea resin (1:3 by wt.) | 4 (total) | 6/46 | KB | 24 | | | |
| | | | 6/46 | DB | | 19 | 24 | Shipworms and pholads. |

TABLE 1 (Continued)

| Item No. | Toxic Used | Wt. of toxic, lbs. per cubic ft. of wood | Exposure— Date | Station | Months of exposure prior to—borer damage: Light | Moderate | Severe | Remarks |
|---|---|---|---|---|---|---|---|---|
| 35. | A proprietary suspension of silica in water | — | 7/45 | KB | | | 2 | Destroyed by worms and pholads. Few L. |
| | | | 7/45 | DB | | | 2 | Destroyed by worms and pholads. Few L. |
| | *C: Synthetic resin impregnants.* | | | | | | | |
| 36. | Melamine resin | 12 | 7/45 | KB | 16 | | | Shipworms. End of test. |
| | | | 7/45 | DB | | 13 | | Mainly pholads, few worms. |
| 37. | Phenol-formaldehyde resin | 10 | 7/45 | KB | 13–16 | | | Shipworms and few *Limnoria*. |
| | | | 7/45 | DB | | | 13 | Large worms, pholads, and L. |
| 38. | Furfural and furfuryl alcohol (1:1) | 25 (total) | 7/45 | KB | 16 | | | Few small shipworms. |
| | | | 7/45 | DB | 6 | | 13–18 | Large worms, pholads, and L. |
| 39. | Chlorinated rubber | 7 | 7/45 | KB | | 4 | 13 | Shipworms, L., and pholads. |
| | | | 7/45 | DB | | 6 | 13 | Shipworms and pholads. |
| 40. | Polyterpene resin | 7 | 7/45 | KB | | 4 | 13 | Shipworms, L., and pholads. |
| | | | 7/45 | DB | | 6 | 13 | Mainly L. Few worms and P. in end of panels. |
| 41. | Coumaron resin A | 8 | 7/45 | KB | | 4 | 13 | |
| | | | 7/45 | DB | | 6 | 13 | Destroyed by worms, some L., few pholads. |
| 42. | Coumaron resin B | 7 | 7/45 | KB | | 2–4 | 13 | |
| | | | 7/45 | DB | 2 | 6 | 13 | Destroyed by worms and *Limnoria*. |
| 43. | Phenol-furfural resin | 9 | 7/45 | KB | | 2 | 4 | Destroyed by shipworms. |
| | | | 7/45 | DB | | 2 | 6 | Shipworms and pholads. Few *Limnoria*. |
| 44. | Polystyrene resin | 2 | 7/45 | KB | | | 2 | |
| | | | 7/45 | DB | | | 2 | |
| 45. | Acrylic resin | 7 | 7/45 | KB | | | 2 | Shipworms. |
| | | | 7/45 | DB | | | 2 | Shipworms and pholads. Few L. |
| 46. | Vinyl chloride-acetate resin | 0.9 | 7/45 | KB | | | 2 | Shipworms. |
| | | | 7/45 | DB | | | 2 | Shipworms and pholads. |
| 47. | Silicone resin | 3 | 7/45 | KB | | | 2 | Shipworms. |
| 48. | Urea resin | (heavy) | 9/44 | DB | | | 4 | Mainly pholads, few worms, no L. |
| 49. | A proprietary resin-surfaced plywood | 0.024 lbs. per sq. ft. | 7/45 | KB | 30 | | | Unattacked at end of test. |
| | | | 7/45 | DB | 30 | | | Unattacked at end of test. |
| | *D: Paint coatings.* | | | | | | | |
| 50. | Antifouling paint 16A—2 coats | Dry film 16% $Cu_2O$ 17% cresol. | 9/43 | KB | 6–8 | | 14 | |
| | | | 10/43 | DB | 6–8 | | 14 | |
| 51. | Antifouling paint 16X—3 coats | Dry film 52% $Cu_2O$— 9% silica | 5/44 | KB | 30 | | | Unattacked. Condition fair. End of test. |
| | | | 6/44 | DB | 18 | | | Unattacked. Condition fair. End of test. |
| 52. | Antifouling paint AF–22—3 coats | Dry film 76% $Cu_2O$ | 5/44 | KB | 30 | | | Unattacked. Condition very good. |
| | | | 6/44 | DB | 18 | | | Unattacked. Condition very good. |
| 53. | Antifouling paint AF–23—3 coats | Dry film 76% flake copper | 5/44 | KB | | 6 | 12 | Fouled badly in 3 months. |
| | | | 6/44 | DB | 6 | | 12 | Fouled badly in 3 months. |
| 54. | An aqueous coal tar pitch emulsion | Dry film 15 gm/sq. ft. | 5/44 | KB | | 3 | 6 | |
| | | | 6/44 | DB | | 6 | 12 | |
| 55. | A "cut-back" coal tar pitch | Dry film 22 gm/sq. ft. | 5/44 | KB | | | 3 | |
| | | | 6/44 | DB | | 3 | 6 | |
| 56. | A solvent-free coal tar pitch | 45 gm/sq. ft. | 5/44 | KB | 6 | 12 | 18 | |
| | | | 6/44 | DB | 6 | | 12 | |

permitted heavy damage in 18 months.

Borer damage to Douglas fir and to red oak panels treated in the same manner was increasingly severe and more rapid.

The antifouling paint used on some of the panels (formula 16A) began to fail after about seven months and permitted severe borer damage within twelve months. After failure of the paint, the preservatives (applied by hot-and-cold-bath) were observed to add to the protection provided by paint alone, as follows:

*Increase in Effective Life of Protection, in Months*

| *Wood* | *Creosote A* | *Cupric Chromate* (3% solution) | *Copper Napthenate A* |
|---|---|---|---|
| Pine | 15 | 3-13 | 2-5 |
| Fir | 15 | 3-13 | 2-5 |
| Oak | 2-4 | 2-5 | 0-1 |

*Dip Treatments.*

All unpainted, dip-treated panels suffered sporadic borer attack during the first months of exposure. However, the three preservatives so applied (creosote A, 3% cupric chromate, and copper naphthenate A) reduced the degree of damage considerably for about ten months. Beyond that time, only creosote showed some slight, irregular value. The effective life of the protection on painted panels was increased by the dip treatments, as follows:

| *Preservative* | *Increase in Life, in Months* |
|---|---|
| Creosote A | 2-5 (over 12 in Panama on pine only) |
| Cupric chromate, 3% | 2-5 (8 in Panama on pine only) |
| Copper naphthenate A | 0 (on red oak) — 3 |

Although the additional protection by this light treatment is for only a few months, the cost and inconvenience of the preservative application by dipping, swabbing, or spraying are no more than for an extra coat of paint and would be well justified for most new wooden bottoms. Similarly, in repainting existing wooden bottoms, application of a preservative by swabbing or spraying on all areas bare of paint would be justified by the added protection.

## EXPOSURE RESULTS FOR SHEATHING MATERIALS

Thirteen different sheathing materials were tested as possible replacements or substitutes for sheet copper sheathing. None appeared completely practical and effective against borers for the exposure period of 18 months (two seasons of borer attack). The materials and observations on the exposure are listed below.

*Two Completely Effective Sheathings.*

Sheet copper and one compressed wood permitted no borer penetration. The wood, "compreg," was a compressed, resin-impregnated, yellow poplar plywood (sp. gr. 1.28, phenolic resin content 15%), with a mixture of resin and very fine silica pressed into the faces.

This "compreg" also provided an excellent base for antifouling paint and might find limited use for special sheathing applications by reasons of its borer resistance and dimensional stability in water, but is probably too costly for general use as sheathing.

Sheet copper, insulated carefully from the steel fastenings permitted only very slight fouling in 18 months. Uninsulated panels fouled completely in 12 months. Un-insulated sheet copper also provided a poor base for antifouling paint.

*Two Partially Effective Sheathings.*

Two other resin-impregnated, laminated woods stopped all shipworms but were attacked by pholad borers. Compreg (as above but with no silica on the surface) suffered slight to moderate damage during 18 months at Daytona Beach. Impreg (same composition, but uncompressed, sp. gr. 0.82) suffered moderate to severe damage in 18 months. No physical deterioration after exposure was observed in either wood.

*Ten Unsatisfactory Sheathings.*

Ten other sheathing materials failed either in protection against borers or by physical deterioration on exposure, as follows:

1. Melamine-bonded plywood was readily attacked by pholads but the gluelines retarded shipworm activity to a considerable extent. Phenolic glues, commonly used in marine plywood, have frequently been observed to have little effect in retarding either borer.

2. A maple compreg (sp. gr. 1.1) was unattacked by shipworms and only lightly attacked by pholads. Some delamination and checking was observed on drying, which would undoubtedly reduce the durability of this compreg in marine use.

3. A bronze-faced compreg (bronze powder pressed into the faces) stopped all borers but provided a very poor paint base. Unpainted panels were heavily fouled, with extremely adherent organisms.

4. Cotton duck saturated with coal tar pitch stopped all but a few pholads. The cloth was severely weakened by immersion for 6-12 months, as were all treated cotton ducks, if not coated with the antifouling paint. The pitch was eroded rapidly in the water.

5. Duck impregnated with antifouling paint (formula 16X, No. 51 in Table 1) stopped all borers and fouling for twelve months. If uncoated with additional paint, the duck was badly weakened by 6-12 months' exposure. The paintability was very good and the painted cloth retained its strength at the end of the exposure (18 months). The paint appeared to have provided a physical barrier to some tendering action by sea water or possibly by decay organisms in the water.

6. Duck impregnated with copper naphthenate stopped all borers for about twelve months only. Unpainted cloth was badly weakened after 6-12 months.

7. Glass cloth stopped all borers until the cloth frayed and broke within a few months. Glass cloth bonded or coated with a rubber or resin might prove more suitable. It was also noted that the glass cloth stopped all borers coming through a "bait" piece of unprotected wood and might thus be of some utility as a sheathing between the planks of double-planked vessels.

8. An abrasive-coated cloth stopped all borers until weakened and torn after a few months' immersion. This cloth also, under a "bait" piece of wood, stopped all borers. It provided a poor base for antifouling paint.

9. A laminated, resin-impregnated paper ("papreg") stopped all but a very few pholads. Under a "bait" piece, a few shipworms were able to penetrate. The papreg proved too brittle for appli-

cation as tested, just tacked onto the wood. A similar fiber layer, bonded onto plywood (No. 49 in Table 1) appeared a more practical application.

10. Galvanized sheet iron, about 0.020 inches thick, stopped all borers of course until rusted through, in six months on some panels.

## PLYWOOD AND TROPICAL WOODS

Another interesting application of silica as borer protection was in the glue-lines of plywood. Addition of 5-20 percent of 200-mesh silica to the glue was found an excellent deterrent to the borers and did not reduce the strength of the plywood. Such silica-glue mixtures should be applicable in normal plywood manufacture and would provide valuable insurance against complete destruction of plywood planking or sheathing on wooden vessels in borer-infested waters. Additional protection would be required for the surface ply, such as antifouling paint or perhaps a thin, resin-impregnated outer ply.

Exposure also was made of a number of panels of Douglas fir plywood, fabricated by gluing up veneers already treated with acid cupric chromate. In the one laboratory fabrication attempted, using a liquid, hot-press, phenolic glue, a rather weak bond was obtained between the treated veneers. However, commercial concerns have since reported success in gluing such treated veneers. The preservative on exposure was found as effective in plywood as in solid wood. After sixteen months at Daytona Beach (almost two full seasons of borer attack), a 1.4-pound treatment had permitted only very slight damage and a 2.8-pound treatment had permitted no damage at all.

Dense tropical woods are frequently proposed as sheathing materials for wooden vessels, particularly where subject to severe abrasion. Many are very abrasion-resistant and some have been reported to have a long life in borer-infested waters. Four tropical woods tested here suffered severe damage by shipworms and pholads within six months at Daytona Beach. The woods are listed below with two domestic woods for comparison of densities.

| *Wood* | *Apparent Density (lbs. per cu. ft.)* |
|---|---|
| Tatajuba *(Bagassa guinaensis)* | 54 |
| Gray ironbark *(Eucalyptus paniculata)* | 72 |
| Araracanga *(Aspidosperma* sp.) | 54 |
| Piquia *(Caryocar parviflorum)* | 52 |
| Red oak | 43 |
| Southern yellow pine | 36 |

## SUMMARY

During the activity in the tropics in the recent war, there was need for a suitable penetrating preservative which would retard marine borer attack enough to prolong the safe life of certain vessels for at least a few months. The preservative would probably have to be applied by non-pressure methods, most likely by swabbing or brushing. That problem was answered at least for immediate needs by the recommendation early in the present investigation that all new wooden bottoms (and bare areas of old bottoms on repainting) be given at least a liberal brush application of one of three preservatives: Creosote, acid cupric chromate, or copper napththenate. Such an application would add

at most several months to the life of the bottoms without any toxic paint or after failure of the paint coating.

Values are reported also for the duration of the protection against marine borers provided by the same three preservatives applied by a more thorough non-pressure treatment, the hot-and-cold-bath method.

Values are reported for the duration of protection (up to 30 months, the longest exposures made) for some thirty toxic materials and thirteen synthetic resins, all injected into the wood by pressure treatments; for seven different toxic paints; for four tropical woods and thirteen other sheathing materials; and for several protective methods for plywood.

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The views expressed by the author are not to be construed as representing those of the Navy Department.

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*Official Department of Defense Photo*

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# ON THE OPTIMUM LENGTH OF A RESONANT RADIO FREQUENCY TRANSMISSION LINE TO MAXIMIZE POWER TRANSFER

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Summary: "Line stretchers" may be used in electronics systems to maximize power transfer. This device is analyzed. Several problems involving the use of transmission lines of adjustable length for impedance matching are solved graphically.

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Naval electronics personnel both ashore and afloat are vitally concerned with the problem of securing optimum performance of electronic systems. If the design capabilities of such systems are to be realized operationally, the problem of impedance matching between elements of electronic systems, such as matching the output impedance of a communications transmitter to the terminal impedance of its associated antenna, must receive careful attention. It is to be emphasized that power generated by a transmitter that is not transferred to its antenna is wasted and thus serves no useful purpose.

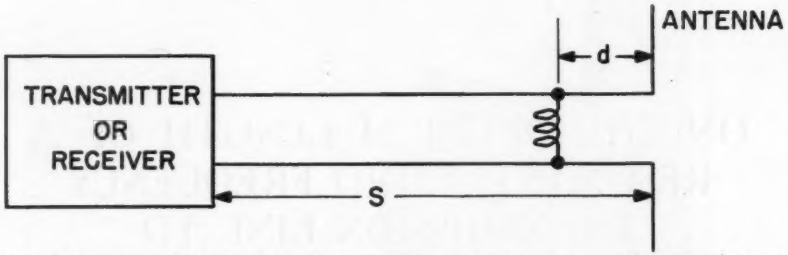



FIG. 1—Transmission line of length s connecting an antenna to a radio transmitter or receiver. At distance d from the antenna a coil is shown connected across the line for purposes of impedance matching.

The intent of the present paper is to present a simple graphical method for determining the optimum length of a resonant radio-frequency transmission line to maximize the transfer of power from the generator to the load under the following conditions:

(a) The characteristic impedance of the line is fixed.

(b) The characteristic impedance of the line is adjustable.

A step-by-step procedure for obtaining optimum impedance match by varying the length or the length and characteristic impedance of a transmission line is discussed employing numerical examples. The theory underlying this method of impedance matching is outlined briefly in Appendix 1 and 2.

Figure 1 illustrates a transmission line of length s for interconnecting a transmitter (whether radar or communications) to an antenna. Alternatively figure 1 might represent a transmission line connecting an antenna to a radio receiving set. At a relatively short distance d measured along the line from the antenna a coil is shown connected across the line for the purpose of impedance matching. This reactor might take the form of a capacitor or an open-circuited or short-circuited transmission line section.

At Naval Communication Stations where the distance s is often very great, every effort should be made to insure that the transmission line is operated in a non-resonant condition to a point as close to the antenna as possible to minimize line losses. The line losses associated with standing wave systems are always greater than those associated with traveling wave systems. Thus the reactor chosen for impedance matching should be of such nature as to minimize the distance d. A traveling wave system will exist over the length of line s-d. Standing waves will exist along the length of line d for without them no impedance transformation can take place.

Now suppose that the transmitter can be physically located in proximity to the antenna, so that the length of line involved is of the order of dimension d, figure 1. Under these circumstances it is desirable to employ a resonant transmission line—on which standing waves exist—to convey power from the transmitter to the antenna. If the line is short line losses are small. Often more power is lost in the impedance matching devices employed to achieve non-resonant line operation than would be lost if the impedance matching device were eliminated, and a resonant feeder system used.

If the exact location of the transmitter (or antenna) is not important, then there is an optimum length of line d (now designated s) to insure maximum power transfer between two

fixed impedances, i.e., the "hot" impedance looking into the transmitter at its output terminals, and the impedance looking into the antenna at its input terminals.

The procedure for determining the optimum length of a resonant radio frequency transmission line to maximize power transfer between generator and load, when the characteristic impedance of the line is fixed, can best be illustrated by a numerical example. Suppose that the transmitter impedance $Z_g = R_g + j X_g$ is 1175 — j495 ohms, and the particular antenna in use has an impedance $Z_R = R_R + j X_R$ of 2,115 + j875 ohms. Let the characteristic impedance $R_c$ of the line be a pure resistance of 500 ohms. (The characteristic impedance of a lossless line is always a pure resistance). Assume that the frequency of operation is 12 megacycles per second which corresponds to a wavelength ($\lambda$) of 25 meters. The result desired is the length of line s required to achieve the best possible match (and hence the maximum transfer of power) between the transmitter and antenna under the stated circumstances. To solve this problem use is made of a chart called a circle diagram, as shown in figure 2. This chart consists of a rectangular coordinate system on a complex plane. Superimposed are two families of circles. The circles which have their centers on the horizontal axis, and encompass the point (1, 0) are called circles of constant $\Gamma$ (gamma) and the circles which have their centers on the vertical axis are called circles of constant $\Phi$ (phi). The circle diagram is based on the assumption that the transmission line is dissipationless. This is a good approximation when the line is short. One finds the ratio $Z_R/R_c$ and $Z_g/R_c$. This process is sometimes termed "normalizing the impedance." The result is $Z_R/R_c = r_1 + jx_1 = 4.23 + j\ 1.75$ and $Z_g/R_c = r_2 + jx_2 = 2.35 - j0.99$.

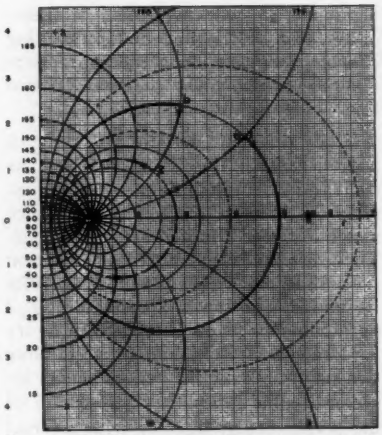


FIG. 2—Circle diagram illustrating solution of an impedance matching problem when the characteristic impedance of the line is fixed.

The value $Z_R/R_c$ is plotted on the circle diagram, using the rectangular coordinates. This locates point 1 on figure 2.

By chance this point lies on the $\Phi$ circle labeled 175 degrees and on the $\Gamma$ circle passing through the point (5, 0) on the horizontal axis. Usually interpolation is necessary. Next the point corresponding to the complex-conjugate of the normalized generator impedance, i.e., $Z_g^*/R_c = 2.35 + j0.99$ is plotted. This locates point 2 on figure 2. This point lies on the $\Phi$ circle labeled 170 degrees and on the $\Gamma$ circle passing through the point (2.85, 0) on the horizontal axis. The angular length of line required is the angular distance taken *clockwise* from point a (which coincides with point 1) to point b, as shown by the heavy line. This angular distance is seen to be 5 degrees plus 170 degrees or 175 degrees. Since 360 degrees of line corresponds to one wavelength, or 25 meters in this illustration, the length of line s required to effect the best possible match between the transmitter and antenna is $175 \times 25/360 = 12.15$ meters. The same result is obtained,

of course, by working from the transmitter end of the line and proceeding *counter-clockwise* along the appropriate Γ circle, as shown by the heavy dotted line.

When the characteristic resistance of a transmission line is adjustable [1] as well as its length it is sometimes possible to effect a conjugate impedance match between the generator and load. To determine when this ideal condition is possible, one proceeds as follows: Plot $Z_R$ and $Z_g^*$ (complex conjugate of $Z_g$) on a complex plane, as shown in figure 3. Draw a straight line between these two points. Erect the perpendicular bisector to this line. The intersection of the perpendicular bisector with the real axis locates the center of a circle which passes through the points $(R_g, -X_g)$ and $(R_R, X_R)$. The intercepts of the circle on the real axis are labeled $R_{min}$ and $R_{max}$. $R_{min}$ is the coordinate of the center of the circle minus the circle radius, and $R_{max}$ is the coordinate of the center of the circle plus the circle radius. Then $R_c^2 = R_{min} R_{max}$. This relation states in effect that unless the circle lies entirely within the first and fourth quadrants no value of $R_c$ exists which permits a conjugate impedance match to be effected between the transmitter and antenna. Furthermore, for purposes of conjugate impedance matching only one value of $R_c$ is possible, i.e., the required value is independent of the length of transmission line employed.

As a numerical illustration of the principle of conjugate impedance matching when the length s and characteristic resistance $R_c$ of a transmission line are adjustable, assume the antenna impedance is $Z_R = 900 - j\ 100$ ohms and the transmitter impedance is $Z_g = 500 + j\ 400$ ohms. ($Z_g^* = 500 - j\ 400$ ohms.) The frequency of operation is

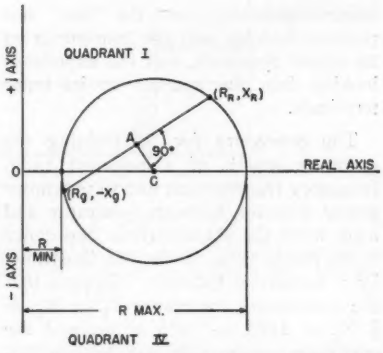



FIG. 3—Circle diagram illustrating solution of an impedance matching problem when the characteristic impedance of the line is adjustable.

12 mc/sec. On carrying out the construction shown in figure 3 for this specific problem, it is found that $R_{min}\ R_{max} = 102{,}400$ (ohms).[2] Accordingly $R_c = 320$ ohms. The ratios

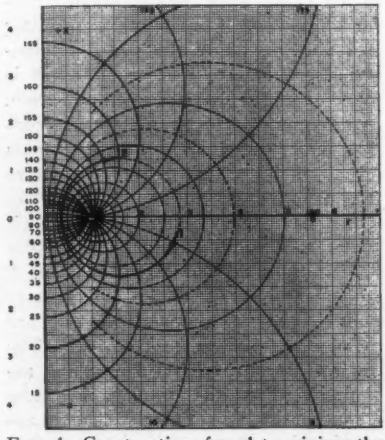


FIG. 4—Construction for determining the value of $R_c$ for use in the problem of impedance matching.

[1] The characteristic resistance of a two wire line, for example, is $R_c = 276 \log_{10} \frac{D}{a}$, where D is the distance between wires taken center-to-center, and a is the radius of the wire used. By changing D or a the characteristic resistance may be adjusted over certain limits.

$Z_g^*/R_c = 1.56 + j\ 1.25$ and $Z_R/R_c = 2.81 - j\ 0.31$. These ratios are plotted on the circle diagram, using the rectangular coordinate system, as shown in figure 4. Point 1 locates the ratio $Z_R/R_c$ and point 2 locates the ratio $Z_g^*/R_c$. By interpolation point 1 is found to lie on the circle $\Phi = 2.8$ degrees, and point 2 lies on the circle $\Phi = 160$ degrees. Observe that both points lie on the same circle of constant $\Gamma$. The angular length of line required is the angular distance taken *clockwise* from point 1 to point 2, i.e., 160 degrees minus 2.8 degrees or 157.2 degrees. Since the operating wavelength is 25 meters, the length of line required to effect a conjugate impedance match between transmitter and antenna is $157.2 \times 25/360 = 10.92$ meters.

## Appendix 1

### Analytical Determination of the Optimum Length of a Resonant Radio Frequency Transmission Line to Maximize Power Transfer When the Characteristic Impedance of the Line is Fixed

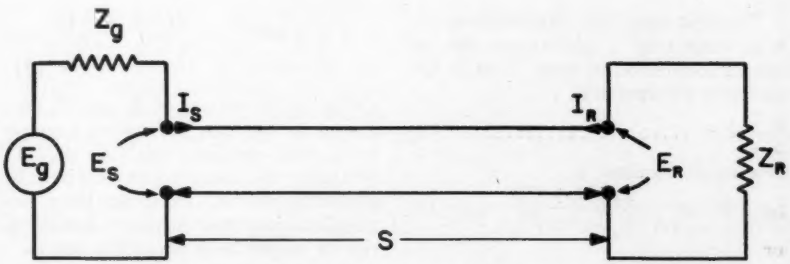



Fig. 5—Pictorial representation of the transmission line notation employed.

The voltage $E_s$ and current $I_s$ at the sending end of a dissipationless transmission line of length s terminated in a complex load impedance $Z_R$ are given by the familiar equations

$$E_s = E_R \cos \beta s + j I_R R_c \sin \beta s \quad (1)$$

$$I_s = I_R \cos \beta s + j \frac{E_R}{R_c} \sin \beta s \quad (2)$$

Here $E_R$ is the voltage developed across the load impedance $Z_R$; $I_R$ is the current flowing in this impedance; $R_c$ is the characteristic resistance of the line, and $\beta s$ is the angular length of the line. $\beta$ has the value $2\pi/\lambda$ where $\lambda$ is the wavelength. Figure 5 gives a pictorial representation of the notation employed. A transmitter or generator is shown connected to the sending end of the line. This generator develops open circuit voltage $E_g$, and has internal impedance $Z_g$. The ratio $E_s/I_s$ defines the input impedance $Z_s$ of the transmission line. That is

$$E_s = I_s Z_s \quad (3)$$

Also, by inspection of figure 5 it is clear that

$$E_g = I_s (Z_g + Z_s) \quad (4)$$

and

$$E_R = I_R Z_R \quad (5)$$

The objective is to maximize the power absorbed by the load impedance $Z_R$, considering $E_g$, $Z_g$, $Z_R$ and $R_c$ to be fixed, and the length of line s to be variable. It is to be observed that the power in the load is given by

$$P = /I_R/^2 \, R_R \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where $/I_R/$ denotes the magnitude of the current in the load, and $R_R$ is the resistive component of the load impedance.

After considerable algebraic manipulation of the simultaneous equations (1) to (5), it is determined that P is given by the expression

$$P = \frac{E_g^2 \, R_c^2 \, R_R}{(A^2 + C^2)\cos^2\beta s + 2(AB + CD)\cos\beta s \sin\beta s + (B^2 + D^2)\sin^2\beta s} \quad (7)$$

with

$$\left.\begin{aligned} A &= R_c\,(R_g + R_R) \\ B &= -\,(R_g X_R + R_R X_g) \\ C &= R_c\,(X_R + X_g) \\ D &= R_g R_R + R_c^2 - X_g X_R \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Note that $Z_g = R_g + j\,X_g$ and $Z_R = R_R + j\,X_R$.

The next step is to differentiate (7) with respect to s, and equate the resulting expression to zero. That is one performs the operation

$$\frac{\Delta P}{\Delta s} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The result obtained is

$$\tan 2\beta s = \frac{2(AB + CD)}{(A^2 + C^2) - (B^2 + D^2)} \quad (10)$$

or

$$S = \frac{1}{2\beta} \tan^{-1} \frac{2(AB + CD)}{(A^2 + C^2) - (B^2 + D^2)} \quad (11)$$

On using the values of $Z_g$ and $Z_R$ employed in the first illustrative example in the text, one finds that (10) or (11) will give the same result obtained by graphical means. In using these expressions improper quadrant identification of angles leads to serious errors.

## Appendix 2

### Analytical Determination of the Characteristic Impedence of a Resonant Radio Frequency Transmission Line, When the Objective Is to Secure a Conjugate Impedance Match by Adjusting the Line Length

To effect a conjugate impedance match, the complex conjugate of the transmitter or generator impedance $Z_g$ must equal $Z_s$, the input impedance of the transmission line when terminated in the load impedance $Z_R$. Refer to figure 5. Thus

$$Z_g^* = R_g - j\,X_g = Z_s \quad \ldots\ldots\ldots (12)$$

Equations (1), (2), and (5) may be used to determine $Z_s$. It has the value

$$R_g - j\,X_g = Z_s = R_c \left\{\frac{Z_R + j\,R_c \tan\beta s}{R_c + j\,Z_R \tan\beta s}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

The expression (13) is complex and therefore may be regarded as a simultaneous equation from which tan $\beta$ may be eliminated.

By equating reals to reals in (13),

$$\tan \beta s = R_c \left\{ \frac{X_g + X_R}{R_R R_g + X_g X_R - R_c^2} \right\} \quad \ldots\ldots (15)$$

and solving

$$\tan \beta s = R_c \left\{ \frac{R_R - R_g}{X_g R_R - X_R R_g} \right\} \quad \ldots\ldots (14)$$

By equating imaginaries to imaginaries in (13), and solving

By equating (14) to (15), and solving for $R_c^2$,

$$R_c^2 = \frac{R_R(R_g^2 + X_g^2) - R_g(R_R^2 + X_R^2)}{R_g - R_R} \quad \ldots\ldots (16)$$

A second relation for $R_c^2$ is obtained from figure 4 by use of elementary analytic geometry. The slope of the line connecting points $(R_g, -X_g)$ and $(R_R, X_R)$ is $(X_R + X_g)/(R_R - R_g)$. The slope of the line AC is then $-(R_R - R_g)/(X_R + X_g)$. Since the coordinates of point A are $(\frac{1}{2})(R_R + R_g)$ and $(\frac{1}{2})(X_R - X_g)$, the equation for the line AC is given by

$$X - \frac{1}{2}(X_R - X_g) = -\frac{R_R - R_g}{X_R + X_g}\left\{ R - \frac{1}{2}(R_R + R_g) \right\} \quad \ldots\ldots (17)$$

The coordinates of the center of the circle are desired. Obviously the center of the circle is at $X = 0$. Upon setting $X = 0$ in (17), and solving for R, one obtains

$$R = \frac{\frac{1}{2}\left\{ (R_g^2 - R_R^2) - (X_R^2 - X_g^2) \right\}}{R_g - R_R} \quad \ldots\ldots (18)$$

Now the radius of the circle is

$$\sqrt{X_R^2 + (R_R - R)^2} \quad \ldots\ldots (19)$$

Since $R_{max} R_{min} =$ $\{$coordinate of the center of the circle$\}^2$ minus $\{$radius of the circle$\}^2$, one has

$$R_{max} R_{min} = R_R \left\{ \frac{(R_g^2 - R_R^2) + (X_g^2 - X_R^2)}{R_g - R_R} \right\} - X_R^2 - R_R^2 \quad \ldots\ldots (20)$$

or

$$R_{max} R_{min} = \frac{R_R(R_g^2 + X_g^2) - R_g(R_R^2 + X_R^2)}{R_g - R_R} \quad \ldots\ldots (21)$$

On comparing (16) and (21) it is clear that

$$R_c^2 = R_{max} R_{min} \quad \ldots\ldots (22)$$

This discussion is significant in that it demonstrates that unless $R_c$ has the value given by (22) it is useless to attempt to obtain a conjugate impedance match between $Z_g$ and $Z_R$ by adjusting the line length s. The mathematical laws governing this phenomenon are inexorable.

*Official Department of Defense Photo*

A United States Ice Breaker

# RUSSIA'S ICEBREAKERS

LIEUTENANT COMMANDER BERNARD M. KASSELL, USN

THE AUTHOR

Enlisted in 1931. Appointed Electrician in 1940, Ensign 1942, and up to Lieutenant Commander in 1949. Served in *Utah, Idaho, Yorktown, Morris* (DD417), *Canopus, Otus, Snowden* (DE246), *Casa Grande* and am now Repair Officer in *Bryce Canyon* (AD36). Served as material assistant on the staff of Commander Destroyers Atlantic Fleet in 1944 and was Electronics Officer at the Fleet Training Center, Norfolk, prior to spending five semesters at Cornell University, where he majored in Russian, the language, economy, history, etc., and took the peripheral subjects which would tie in to the picture. Became interested in Russian shipbuilding when he found that little or no collected material existed on the subject. Since that time, two years ago, he has found a considerable amount of material available. All that is necessary, evidently, is a lot of digging for sources, one of which leads to another, and the plugging to do the translations. At the moment he is trying to find the time to do some translations so as to round out a paper started on the shipbuilding industry during the first five-year plan, and then branch out into the other plans so that the entire picture may clear up a little. Has been awarded the area ribbons, all three, the Pacific with one star for having been in the Philippines when the war started, the Philippine Defense, Occupation and China Service medals, Defense medal with fleet clasp, World War II Victory medal and the enlisted good conduct with one star. Most of his service has been in engineering or materiel work, although he was executive officer and later commanding officer of the *Casa Grande*.

*". . . the icebreaker is the first in this work of ours . . ."*
M. Lavrov (President of the North Sea Route Co-operative Development Concession)

The shores of the Soviet Union are washed by many oceans and seas, but it is only in the north that Russia is the undisputed master. Russia controls an Arctic coastline 15,000 or so miles long —and she controls it with the aid of her icebreakers, powerful and sturdy craft fitted with good technical equipment and aided by radio and meteorological stations scattered throughout the Arctic, observation posts, fueling stations and aircraft, all of which are manned by experts in their particular fields.

Since the days of Peter the Great, and even before that time, the Russians have utilized the waterways for commerce, exploration and, in many instances offensive operations against an enemy, real or supposed. But there was always, in the background, the knowledge that



A United States Ice Breaker

the waterways, not only the rivers, but, more importantly, the seas, would yield to the influences of the rigorous winters. The ice, which blankets the rivers, renders those in the European part of Russia useless for navigation for from four to six months out of the year, while the Asiatic waterways, the Ob, Yenisey, Lena and Amur, emptying into the Arctic Ocean and the Sea of Okhotsk, are useless for from five to seven months. The oceans vary in closure time, but the most important ocean route of all, the Arctic, is normally open about four months out of the year.

It is this ocean, with its economic and strategic benefits and advantages, which has been the concern of Russia for many years. As early as the middle of the 17th Century Russian merchants were eager to utilize the northern waters to transport their furs, for the further the Eastern penetration, the more valuable were the furs obtained. The possibilities of a Northern Sea Route, leading through the Kara Sea to the mouths of the Ob, in the Ural region, and Yenisey, in the eastern Siberia region, were pointed out as early as 1875 by Eric Nordinshield and reiterated by Fridtjof Nansen in 1913. Development, however, languished until 1921, when the Northern Commercial Route Company (Komsevput) was formed to organize systematic shipping by way of the Kara Sea and to develop production in the north by building plants to work up export products. The Kara Sea expeditions increased their freight handle as follows.[1]

| *Year* | *No. Ships* | *Freight Transported* (metric tons) |
|---|---|---|
| 1921 | 5 | 8,317 |
| 1926 | 5 | 19,168 |
| 1927 | 6 | 24,428 |
| 1928 | 8 | 29,378 |
| 1929 | 26 | 75,000 |
| 1930 | 46 | 195,000 |

Perhaps the best indicator of the feasibility of the route is expresesd by the insurance rate; 6 percent in 1914, it dropped to 1 percent in 1928 and to 0.5 percent in 1931.[2]

The significance of the opening of the Northern Sea Route was expressed in the statement that:

> "The establishment of regular water communication between Pacific ports and the Lena River . . . should play an especially important part in the development of the rich natural resources, particularly gold and platinum, in the export trade in furs and fish and in supplying the population [of the Yakutsk Autonomous Republic] with provisions and hunting equipment . . ."[3]

But economics was not the sole consideration. The experiences of the Baltic squadron in the Russo-Japanese War brought home to the strategists of the time how much more advantageous it would have been to have sent their warships through Russian waters to the East, without the necessity of exposing them to enemy action or hostile treatment on the way.[4]

Yet it must be conceded that the immediate purpose of the development of the northern route was to exploit the advantages of a through route along Russian shores for the purpose of tapping the hinterlands of the great rivers which empty into what was to become known as the Northern Sea Route. Navigation was, and still is, difficult. The navigation season is all too short for careless shiphandling, slipshod methods of loading and unloading ships, and laxity in administration. A season's work must be accomplished in the July to October period.

In order to cope with the problems which arose with monotonous regularity, changes were made in the administration, and the group which finally emerged in 1933 as the controlling body was known as the Central Board of

Administration of the Northern Sea Route (Glavsevmorput). This organization was charged with the complete administration of the affairs of the Soviet Arctic, doing its own planning and having its own budget. It was to this organization that control of the icebreaker fleet was passed.

This fleet, hardly adequate for the harbor needs of the country, was far from adequate for the task assigned to it—the maintaining of a right of way through the Arctic ice. This inadequacy was brought out when figures, released by the Soviet government, indicated that, in 1923, the traffic of goods of all the Russian ports had not attained more than 21.4 percent of the total of 1913. Russia's grain export program of 1923, desperately requiring fulfillment in order to finance the country, pointed up the imperfections of the Russian ports, and *Economicheskaia Zhizn* (Economic Life) listed five major improvements to be made. The fifth of these, "to insure freedom of navigation during the winter season with the help of large icebreakers," is pertinent, for it points up the fact that the importance of these units was not overlooked by the planners. However, other than dispatching *Litke* and *Markarov* and three smaller icebreakers to the Black Sea to keep traffic open between Odessa and Nikolaev, nothing further was done to implement the plan.[5]

Concern over a lack of icebreakers continued to haunt the planners, who expressed the situation in the main northern port, Leningrad, in these words:

> ". . . The capacity of Leningrad port is limited by the fact that it is frozen during several months of the year. However, the use of icebreakers has resulted in lengthening the navigation season by as much as two or three months. The freight turnover during the icebreaker season amounts, on the average, to about one-fifth of the yearly freight turnover. In order to extend the work of keeping the harbor clear of ice, orders have been placed for the construction of additional icebreakers of modern type . . ."[6]

It is, therefore, understandable that the construction of icebreakers was at the top of the list of needed units compiled by the new administration of the Northern Sea Route. Drigo, one of the *rapporteurs* on the Glavsevmorput, pointed out that the mastering of the Northern Sea Route required the creation of a powerful fleet of icebreakers, equipped with the most modern navigational equipment. He further pointed out that the existing fleet failed to satisfy the demands placed upon it by the growing cargo turnover along the route.[7]

This existing fleet, an inheritance from Imperial Russia, in 1934 was composed of the following vessels, which are divided into two classes.[8]

This was the group of vessels charged with maintaining traffic along the Northern Sea Route. To its credit is the fact that it was reported able to accomplish from eight to ten through passages along the route annually.[9] And to this group was given the most attention. *Sadko, Lenin, Litke, Krasin, Yermak* and *Malygin* were all overhauled. But even more important, however, was the fact that a ship construction program was, finally, delineated. This program required that the icebreaker fleet be strengthened numerically and that transport ships, strengthened for work in the ice, also be built.[10]

| Name | Year Built | H.P. | Displacement (tons) | Fuel Store (tons) | Cargo Capacity (tons) |
|---|---|---|---|---|---|
| **A. ICEBREAKERS** | | | | | |
| *Krasin* | 1917 | 10,000 | 8,750 | 2,665 | — |
| *Yermak* | 1899 | 9,500 | 8,250 | 2,650 | — |
| *Lenin* | 1917 | 7,980 | 6,000 | 1,200 | — |
| *Litke* | 1909 | 7,000 | 3,028 | 750 | — |
| **B. ICEBREAKING STEAMERS**[a] | | | | | |
| *A. Sibiryakov*[b] | 1909 | 2,000 | 2,600 | 292 | 808 |
| *V. Rusanov* | 1908 | 2,200 | 2,600 | 292 | 808 |
| *G. Sedov* | 1909 | 2,360 | 3,056 | 285 | 1,065 |
| *Malygin* | 1912 | 2,800 | 3,200 | 300 | 650 |
| *Sadko*[c] | 1913 | 3,500 | 3,350 | 250 | 950 |

a. These vessels, erroneously listed in various publications as "icebreakers," are cargo types, specifically strengthened for operations in ice. Drigo points out the fact that their small carrying capacity was of little assistance and that more capacity was needed. In addition, Soviet publications distinguish between icebreakers (*ledokoli*), ice-cutting ships (*ledorezi*), and the above, designated as *ledovoi parakhod.*

b. Abandoned in Kara Sea in November 1936. Salvaged by *Epron,* the Soviet salvage organization, during the summer of 1937.

c. Struck a rock in the White Sea and sank in 1913. Salvage was begun in the spring of 1932.

Thus, in 1934, we find the beginning of the construction of icebreakers in Russia. For all her need, and despite the conditions along her coasts Russia had never before attempted the construction of this type of ship.[11] Every one of the ships in service, in 1934, were of foreign build, despite the fact that, *circa* 1865, a Russian shipowner named Britneff, or Britnev, had reconstructed the bow of the steamer *Pilot* in such a way that she could be driven onto the ice in the hope that she would break it by her own weight. This experiment had led to the planning and building of *Eisbrecher I,* launched in Germany in 1871, the first specially designed icebreaker to be built.[12]

Planning was undertaken on three types of ships to be used in the ice. The first type was an icebreaking steamer, which proved the easiest to work out, for there was to be laid down a ship comparable to those already working in the ice. Various alterations and changes were made, however, to overcome the defects which had been noted in those in use. The second type was to be a Diesel-electric icebreaker of 12,000 brake horsepower. The third type was to be an icebreaker of the *Krasin* type.[13]

The icebreaking steamer, the *Sevmorput No. 1,* was the result of a technical study of the behavior of the hull of the ill-fated *Chelyuskin,* then on its final voyage. The designers maintained communications with the ship and incorporated in their plans the reports they received. These reports included the influences of varying ice pressures on the hull. The design, claimed to have been worked out by the best engineering-technical brains in the shipbuilding industry, was approved by the administration of Glavsevmorput, and the ship was laid down. A special commission was set up to supervise the building, as well as all future building, and a decree of the Council of People's Commissars of the U.S.S.R. of July 20, 1934, directed that construction be completed in time for the ships to take part in the navigation season of 1937. That this deadline, giving the builders approximately three years, was not met, and the reasons for failure to do so, will be detailed below.

The Marti Shipbuilding Yard, in Leningrad, was assigned the task of building two Diesel-electric icebreakers, each of 12,000 brake horsepower. The only ship in the world, at the time, which was comparable to that designed

by the Soviet naval architects was the Swedish *Ymer*.[14] Considerations which led to the planning of Diesel-electric types were along these lines:[15]

1. The substitution of internal combustion engines for steam machinery considerably decreases the expenditure of fuel per unit of power. For example, if fuel expenditure (coal) for a steam-driven icebreaker per hosepower hour is 0.8-kg., then for a Diesel-electric type the expenditure of oil figures to be only about 0.2-kg.
2. The lesser fuel expenditure would considerably increase the cruising radius of the icebreaker, enabling the type to work in the Arctic for 52 days without fuel replenishment. This was compared with 27 days for the *Krasin* type.
3. Main engines can be started and stopped quickly; the vessel thus adapting itself to the conditions of work with a flexibility unattainable with steam machinery.
4. Electric motors for propulsion permits the construction of ahead and astern controls in the immediate vicinity of the captain's bridge. This enables the captain, while conning, to have direct control of the engines, thus avoiding the errors which crop up during relaying of orders.
5. Electrical transmission utilizes power more advantageously than steam. The result is a reduction in the number of propeller revolutions, an important feature during maneuvering in the ice.

But the most important feature to be built into these new vessels was concerned with the provision of a large cruising radius, in order to eliminate the necessity of calling at fueling bases to refill bunkers while en route.[16] The two icebreakers to be built by the Marti Yard were assigned the names *Kirov* and *Kuibyishev*.[17] Each vessel was to be equipped with four Sulzer-type engines of 3000-hp. each, operating at a constant speed of 300-rpm. Five, 500-hp. auxiliary Diesels were to complete the engine installation. The Sulzer-type engines were selected for their relatively small weight, 22-kg./hp., as compared with 133-kg./hp., for other types available at the time.

The principal characteristics of this class, as cited, were to be:

| | |
|---|---|
| Length at waterline | 101.0 meters |
| Length overall | 109.0 " |
| Beam at waterline | 21.2 " |
| Beam overall | 22.3 " |
| Normal draft | 7.25 " |
| Maximum draft | 8.4 " |
| Normal displacement | 8,330 tons |
| Maximum displacement | 10,250 " |
| Engine horsepower | 12,000 brake |
| Number of propellers | 3 |
| Distribution of power | 1:2:1 |

Several innovations in icebreaker construction were incorporated in these vessels. Among the more important was the unequal distribution of power to the three shafts. In order to safeguard the mobility of the ships, in the event of damage to the propellers or shafts, or both, it was decided to furnish one-half of the total power to the center shaft, and one-quarter to each of the two outboard shafts.[18] This decision was based on observations which indicated that dam-

age occurred more frequently to outboard propellers. In addition, a special trunk was to be fitted over the amidships propeller so that, in the event of damage to that unit, blades could be changed from within the ship.

Towing winches were to be provided in the stern, to be used in the event of necessity for towing ships being convoyed through the ice. The stern was to be recessed so that the tow could be snugged up astern if necessary.

In order to alleviate the hardships connected with duty in these types of ships, Soviet designers were reported as having incorporated "quieting" tanks, which were to reduce considerably the maximum angle of roll. Small auxiliary boilers were to be installed to furnish steam for heating. The forecastle, in order to increase crew comfort and to overcome excessive wetness forward, was to be "large." Quarters for personnel were to be laid out "artistically," and were to include cabins for the crew, two men to a cabin, a Red Corner,[19] sick-bay, etc. This concern for the crew was explained, ideologically, as follows:

> ". . . The icebreaker *Krasin* was built by decree of the Tsarist Government in Newcastle. . . . No attention was paid to crew accommodations. The icebreaker *Krasin* has, therefore, uncomfortable common berth decks as a legacy of the old, bourgeoisie relation to man, to sailors. In the new icebreakers . . . there will not be built a common berth deck for the accommodation of the crew, but comfortable cabin arrangements, account being taken of the cultural daily needs and requirements of the soviet sailor. . . ."[20]

Whereas previous icebreakers had no facilities for carrying freight, these new icebreakers were to be provided with holds capable of stowing 300-tons of cargo.

The various branches of science were not forgotten, as laboratories for work in biology, hydro-chemistry, physics, meteorology, subsoil, and other related subjects were to be provided, together with the necessary equipment. The importance attached to science by the Soviets may be seen from the report that a Hydrographical Technical College, under Glavsevmorput, was opened in Leningrad in 1935. The function of this College was to train qualified experts, engineers, navigators, etc., for work in the Arctic regions. The course, covering a five year period, was to engage students in the study of navigation, geography, geodesy, astronomy, meteorology and other allied sciences. Students were to obtain practical experience by participating in the various expeditions, and lecturers were to be prominent Arctic explorers and scientists.[21]

In addition to the most modern navigational instruments, such as the speed log, echo-sounding equipment, sounding lead, gyro-compass, etc., two aircraft were to be assigned to each vessel. Launching, when water conditions were unsuitable, was to be by catapult; booms for recovery purposes were also to be provided. Aircraft use was not new in the Arctic, however. According to Soviet data, all expeditions to the Arctic, both overland and by sea, included planes in their equipment as early as 1928. It was pointed out that:[22]

> ". . . Ordinarily the range of vision of a ship is limited to ten or twelve miles. When the ship enters areas covered with large masses of floating ice it is often difficult to decide which course to follow in order to get out into open water. With the help of a hydroplane, however, a range of vision of fifty miles or more can be obtained. . . ."

By 1935 planes were permanently assigned to the polar regions to help in surveying the icefields, in hydrographic work, and in carrying out routine search procedures. Aerial photography was another task assigned, as well as the establishment of communications with the polar radio stations, such as North Cape,

Wellen, Wrangel Island, Dixon, etc., during the winter seasons.[23]

The extensive experience of the Soviets with their icebreakers resulted in the aforementioned changes, as well as changes in the hull design of the icebreakers which were to be built. These changes came about as the result of detailed observations by scientists and engineers of the actual working qualities of the various types of vessels in use in the Arctic. It was pointed out[24] that selection of the hull form is of great significance and influence on the icebreaking properties of ships. Krysov divided vessels used in the ice into two types, according to bow shape, calling them either icebreakers or ice-cutters. He explains that icebreaking ships, those with a bow in the form of a wedge in both the horizontal and vertical planes, are able, with the assistance of their powerful engines, to ride up on the ice shelf in front of them, thus utilizing their weight to crush the ice. This method of getting through the ice was explained as being more efficient than attempting to batter one's way through, particularly since, in the cold Arctic waters shattered ice acted differently than did the ice found, for example, in warmer waters and climates. For this reason the ice-cutting bow form was almost never encountered.

Thus the icebreaking steamers of the usual commercial type *(Sibiryakov, Rusanov, Sadov)* are not the operating equals of *Sadko* and *Malygin,* which have a raised bilge with a large radius of curvature. Ice damage to the first three was greater than to the latter two, but groundings and collisions were the cause of even greater damage to all. From observations made after groundings, it was discovered that the double bottoms were a source of great protection. *Sadko* and *Malygin,* whose bilge keel projected far out from the double bottom, suffered more extensive damage than did the others.

Stability was given serious consideration as well. The conclusion was reached that, for ships destined for working in the Arctic ice, the horizontal moment, curved during compression of the ship by ice, can have the same magnitude as the vertical moment. Criticism was leveled at the designers for paying more attention to the side assembly of the vessels and not enough attention to the basic framework, the diametrical shape and the bulkheads, for these parts were found to work intensively when the plating was deformed by the ice pressure.

This deformation, it was pointed out, had to be foreseen and provided for in order to design a framework which would be strong enough to absorb local stresses without cracking and buckling. It was found that the bulkheads of icebreakers were subjected to stresses which constricted them considerably. As the plates were buckled by the ice, the stresses created hastened bending of the side bulkheads crosswise of their plane. These forces created crumbling of the extreme plates of a bulkhead, disturbing the riveted joints and causing leakage to occur, which in turn had an adverse effect on stability. One means of eliminating rivets, the use of electric welding, was utilized, but even welded seams were, it developed, subject to rupture. As the external plates work, under compression by the ice, as a single whole, the pressure in any one place on the sheathing creates stresses which are transmitted to the rigid connections, and the result is rupture of the horizontal and vertical seams. But these ruptures very rarely, in the experience of the Russians, extended along the entire length of the seams, a fact which Russian engineers credited to the plasticity of the ice, its relative weakness and the fact that the pressure is distributed proportionately. Hence, Krysov reasoned, the stoutness of the external plating is not, by itself, an important factor in the safety of ships operating

in the ice, although, he pointed out, those vessels with the stoutest sheathing would be more active in the ice.

Since the longitudinal seams, during separation, meet with resistance from the frame members, to which the rupturing stresses are communicated, the frames, apart from their fundamental work, must also compensate for insufficient strength of the longitudinal seams. Characteristic damage to ships which had cruised in the ice prior to the building of these Soviet designed vessels was rupture of the first plates in the ice belts (at the garboard strakes), disarray of the riveted joints, breaking of the solidity of the garboard strakes and the seams attached to them, and rupture of the electric welding. The conclusion was reached that the plating had to be strengthened along its external perimeter, in particular at the stem and also at the transverse bulkheads. This, in turn, required that the stem itself possess adequate strength.

The builders of *Yermak*,[25] understanding the need for strengthening the stem, introduced a partial diametrical bulkhead in the vicinity of the fore-peak. Krysov criticized Soviet builders for failing to exploit this idea, pointing out, that during the refit of *Litke*,[26] the plating thickness was doubled and the transverse assembly reinforced ten times—but that only trifling alterations were made to the stem, even though reinforcement of the stem and its interconnecting members into one structural whole, together with the building of a double bottom, would have been many more times helpful. The traditional views concerning bow construction, if rejected, Krysov felt, would increase the ability of Soviet ships to work in the ice.

Rudder damage was another difficulty taken under study, in view of the repeated damage to blades, twisting of the rudder head, etc. While no solution to this problem was offered, it was suggested that a new type of construction was necessary—construction of the rudder assembly of *Litke*, which had incurred the least damage, being suggested for study.

With regard to actual construction work, in view of the fact that riveted joints of ships which worked in the ice became disarranged more rapidly than those of other types of vessels, care was suggested in the manufacture of the rivets, in order to avoid rivets which "hammer like valves" after becoming loosened. Even greater care was advocated in alignment of rivet holes, attention to the use of proper sized rivets, and, finally, it was cautioned that the quality of the riveting had to be of the highest type.

It is worthy of note that the efficacy of caulking and corrosion was not overlooked in this study. To the Soviet builders, who may or may not have been of the best, it was shown that study and tests had proven that the products of corrosion, formed between the surfaces of the steel plates, stoppered all crevices, and that this type of seal could not compare with the results to be obtained from caulking. But, it was cautioned, seams must be drawn tight, and no play between contiguous surfaces, or of the rivets in their holes, was permissible. Caulking, it was stated, was necessary, not to seal, but actually to preclude the loss of the products of corrosion because of insufficient tightness of the overlap of the selvage.

In conclusion, Krysov pointed out that the demands placed upon ships which were required to work in the Arctic were of a different nature from those made of ships in use for ordinary work and, therefore, it behooved Soviet designers to use their ingenuity because, however novel the type of design, it offered no greater difficulty of solution than that of the development of any new design.

Despite this admonition, existing types proved to be the best pattern for the designers to follow, with modifications, of course, in laying out the new ice-

breakers. In addition to the Diesel-electric type, the Soviet Government, by its decree of July 20, 1934, concerning the expansion of the activities of Glavsevmorput, directed Narkomtyazhprom[27] to get on with the building of four "line" icebreakers of the *Krasin* type. Plans for this type took into consideration the deficiencies and structural faults of *Krasin,* and attempted to eliminate them.

Superheated steam machinery was to replace the saturated steam type, to result, it was hoped, in an overall economy of 0.15-kg. of fuel per horsepower per hour. Watertightness was to be improved; icebreaking qualities were to be stressed; cranes were to be electrified; hull strength increased; heeling tanks enlarged, fuel expenditure decreased and cruising radius increased. It was hoped that the horsepower developed would be about 10,000.

Four ships of this type were planned. Two, *Stalin* and *Molotov,* were assigned to the S. Ordzhonikidze Works in Leningrad on the Baltic, and two, *Kaganovich* and *Shmidt,*[28] to the Marti Yards in Nikolaev.[29] *Stalin* was, for obvious reasons, designated flagship of the icebreaker fleet. In power and quality these vessels were to surpass not only *Krasin,* but *Yermak* and others. But it must be noted that Russian claims in this direction are not as impressive as might be supposed, particularly in view of the fact that *Krasin* was built in 1917, while *Yermak* was built in 1898. The very fact that these two have been able to absorb the pounding of Arctic ice for all these years is indeed a tribute, not to the Russians, but to their English designers and builders.

Some idea of the relative dimensions of the model and the new vessels may be obtained from these figures:

| | *Stalin Class* | *Krasin* |
|---|---|---|
| Length | 347.8 feet | 315 feet |
| Beam | 75.5 feet | 68.9 feet |
| Draft | 22.0 feet | 26 feet |
| Displacement | 11,000 tons | 9,000 tons |

It is interesting to note that the new class was to be of shallower draft than the older vessels. According to Drigo:[30]

> ". . . In particular there was taken into account the depths of the northern seas and rivers. The planned icebreakers had to be given dimensions which would ensure their through passage along the Northern Sea Route and give them the necessary cruising radius in the polar sea. . . ."

In order to strengthen the hulls, intermediate frames, in addition to the basic frames, were to be installed; frame spacing was to be slightly over twelve inches (310-mm). Frames were of channel, Nos. 24 and 30 to be used,[31] and were to extend to the main deck, except in the bow, where it was planned to extend them to the upper deck. The decks, metal throughout, were to be four in number (lower, main, living and upper), and were to carry, together with the framing, the longitudinal and transverse stresses set up in the ship. In addition to the basic frames, there was to be a whole series of longitudinal connecting stringers. Taken overall, this type of construction was considered to be adequate enough to enable the vessels to carry out their tasks successfully.

The external plating was to consist of twelve belts, four of which were to be doubled. Plate thickness was reported as being slightly over three-quarters of an inch to slightly less than one inch (20 to 25 mm), which would make the ice belt between one and one-half and one and three-quarters inches (40 to 45 mm) thick.

Hull outline was classed as ovoid, in order to protect it from being crushed by the ice.

The three sets of triple expansion engines,[32] with a total of 10,000 horsepower, were to be furnished with steam from nine boilers, each to have a diameter of fifteen and three-quarters feet and a heating surface of 2690 square feet, installed in four firerooms, which were to be equipped with Gouden forced

draft blowers and ash removal equipment. Surprisingly enough, there appears to have been no attempt made to either utilize oil fuel, nor to convert these vessels to oil burners. It may be assumed that coal deposits along the Northern Sea Route make it advisable to use this type of fuel, thus eliminating the necessity for transporting oil northward from the oil fields and of setting up fuel storage facilities.

Electrical equipment was to be operated from the output of two, 50-kw., turbo-generators. A 25-kw. steam dynamo was to be installed for use at anchor, and, in addition, a 12-kw. emergency Diesel generator was to be provided.

Rudder and anchor gear were to be steam operated, but four electrically operated cranes, of 3-tons capacity each, and two cranes of 1.5-tons each, together with electric towing winches, not to mention other electrically operated machinery, casts some doubt on the correctness of the information concerning the size of the main generators. Obviously, not all of the electrical equipment could be operated at the same time, hence the question as to why such an extensive crane arrangement remains unanswered.

All the icebreakers were to be fitted with special heeling systems, to assist the vessels in rolling themselves in the ice when occasion demanded. In the steam-driven type, piping, leading to all parts of the ship, was to be 500-mm in diameter, reaching, in places, 850-mm. Combination ballast-salvage pumps with a capacity of 1500-tons per hour were to service this system.[32A]

Of more than passing interest is the description of living quarters in the steam-driven type:

> ". . . Special artist-architects were commissioned by the plants to work out designs for the details of the ship's living spaces, such as artistically laid out cabins for the crew, mess halls and Red Corners. The spaces are individualized by fine woods, walnut, beech, speckled (curled) birch, and others. Comfortably appointed cabins for the officers and crew, the absence of the limited orlop decks, the presence of a sound motion picture installation, and a whole series of accommodations, such as steam baths, bathtubs, showers, sickbay, isolation ward,[33] electric meat grinders, potato cleaners, dough mixers, and other equipment, will create maximum conveniences for equipment, scientific workers and other passengers of the icebreaker. . . ."[34]

Nor was the experience of *Krasin*, in 1934, overlooked. This vessel was required to pass through the Panama Canal on her way to salvage what was left of the *Chelyuskin* equipment, and, having no refrigeration equipment, found the storage of fresh provisions virtually impossible in the tropics. Hence, the *Stalin* class was to be fitted with a carbonic-acid type refrigeration installation capable of handling "10,000 small calories per hour" for the safeguarding of perishable products, such as meat, butter, vegetables and fish.

Since these vessels were to be completed to take part in the navigation season of 1937, virtually all available facilities were enlisted in the drive for the accomplishment of this aim. More than twenty plants were to take part in the construction; the metallurgical plants of Zaporozhe, Mariupol and Taganrog furnishing metals, the Marti Works in Nikolaev the rudders, Russky Diesel the engines, Moscow plants the pumps and compressors, Elektosila and the Kharkov electro-mechanical plants the electrical equipment.[35] The S. Ordzhonikidze plant was to build the steam engines for the *Stalin class*.[36] Yet, with all this mobilization of industry, work progressed ineffectually.

According to the plan, those ships, supposedly laid down in 1934, a year later, by the end of 1935, were to have

reached the following stages of completion.[37]

*Sevmorput No. 1*.....42%
Diesel-electric type .....20%
Steam type (*Stalin* class) ..25-30%

Drigo expressed the fear that the plants would fail to complete the ships on time (by the navigation season 1937) and gave as his reasons the reports of the supervising engineers, who asserted that several of the plants were insufficiently mobilized. Little, if any, interest was being shown in the work, particularly the work in connection with *Sevmorput No. 1*. The Marti Yard, in Leningrad had, in 1934, the year the keels were to have been laid, not yet placed orders for the necessary metals, equipment and machinery. This situation held with regard to the orders and the conclusion of contracts with the plants which were to furnish the machinery for the Diesel-electric type. The only bright spot in an otherwise gloomy picture appeared in connection with the steam-driven type, work being reported as going on "intensively," both in the Baltic Plant and in the Nikolaev Plant. Yet even these particular vessels were not certain of completion on time; delivery of the needed metals was poor and tended to slow down the tempo of work. It was pointed out that:[38]

". . . Up to the present time [September 1935] there does not exist the necessary clarity of correlation between the customer, Sudoproekt,[39] and the plant-builders. Instead of a businesslike and urgent solution of all questions, the factions continually and unnecessarily correspond with each other, hindering construction all the more.

"This summary indicates the fact that the construction of all ships is going badly. All the organizations involved in the construction of the icebreaker fleet have to reorganize their work and change from the torrents of paper correspondence and arbitrary discussions to concrete practical work in order to guarantee the fulfillment of the decision of the Party and the Government and to give to the country the icebreaker fleet on the established date."

More than six months later, in April 1936, it was pointed out that the decree of the Council of People's Commissars of the U.S.S.R. and the Central Committee of the All-Union Communist Party (Bolshevik) of July 20, 1934, made it obligatory for industry to finish the construction of the vessels for the navigation season of 1937, and the conclusion was:[40]

". . . Nevertheless, construction is going greatly retarded. It is being retarded particularly by the dilatory and incomplete supply of metal by the Ilich Plant in Mariupol, the Dzerzhinsky Plant in Zaporozhe, and the Andreev Plant in Taganrog. . . ."

In actual fact, these vessels did not get into production until 1935, and two years later, in 1937, the year in which they were scheduled for completion, not a single Russian-built icebreaker or icebreaking steamer was in service.

Nor can this failure be laid to lack of funds. For the three years from 1933 to 1936, Glavsevmorput was allotted 165,000,000 rubles,[41] and in 1937 shipbuilding in the Arctic was allotted 45,830,000 rubles. Of the money spent, the icebreakers of the *Stalin* class accounted for 19,800,000 rubles, while the *Sevmorput* type took 9,200,000 rubles.[42] The total cost of building the icebreakers and icebreaking steamers, in Leningrad alone, was 57,000,000 rubles.[43]

According to the plan for 1937, the sum of 150,700,000 rubles was appropriated for the needs of Glavsevmorput. Of this sum, almost 110 million rubles, or over 70 percent of the total investment, was assigned for maritime transportation. Shipbuilding was assigned almost 48 million rubles, the Murmansk shipyards alone receiving 35 millions.

The building of ports was to cost almost 4 millions, hydrography almost 3 millions and communications over 4 million rubles.[44] Conversion into dollar values is difficult because of the fluctuations in the value of the ruble during these years, but some idea of these costs may be obtained by converting at the rate of $0.51 per ruble, the value which pertained throughout most of the period. This does not, of course, present an accurate picture, primarily because of the internal manipulation of the value of costs and prices within the Soviet Union by the government.

For this expenditure, by no means a small one, Belousov, Chief of the Glavsevmorput's Leningrad District, pointedly stated the fact that results were not up to expectations:[45]

> ". . . One of the most important tasks of the Leningrad District Administration in 1937 is to complete the construction of the icebreaking vessels begun in 1935. . . . Up to the present our industry has not yet produced a single icebreaking ship . . . in spite of the vital importance that these new icebreakers join the fleet as soon as possible, their construction is progressing at an unpardonably slow rate of speed. Construction of the icebreaking steamers is only slightly faster. They were only 20 percent ready on January 1, 1936. On January 1, 1937, work has reached 41 percent of readiness. At the present time we are facing the danger that their construction will not be completed as provided in the plans of the Government, *Stalin* in March, *Molotov* in June and *Sevmorput* in July of 1937. Under such circumstances, it is difficult to count on the participation of even one of these vessels in the navigation of 1937. . . ."

M. Belousov's worst fears were realized, for although *Stalin* was launched August 13, 1937, with all the speeches and fanfare in the press appropriate for such an auspicious occasion, the vessel was not commissioned until September, 1938. *Molotov* was later still. *Kaganovich*, although launched in April of 1937, without fanfare, by the way, did not hold machinery trials until October, 1938.[46] These two appear to have participated in the last phases of the 1938 season, and all of the season of 1939. *Molotov* and *Shmidt* were not expected to participate until even later.

By 1940 the Russians were able to publicize the fact, without fear of contradiction, that they had the largest fleet of icebreakers in the world, not only in numbers, but in total horsepower as well. Some idea of the situation prior to the outbreak of World War II, may be obtained from the following table:[47]

| *Country* | *No. Icebreakers* | *Total Horsepower* |
|---|---|---|
| U. S. S. R.[a] | 40 | 122,900 |
| Germany | 12 | 9,160 |
| Sweden | 11 | 32,700 |
| Denmark | 9 | 15,500 |
| Finland[b] | 6 | 23,700 |
| Canada[c] | 4 | 20,400 |
| U. S. A. | 1 | — |

[a] Including *Molotov* and *Shmidt* (renamed *Mikoyan*).

[b] Five were former Russian icebreakers: *Tarmo Samro, Avans* and others.

[c] One the former Russian icebreaker *Hercules*.

Engineer A. Kilesso was unimpressed with the above-listed fleet, however.[48] In his opinion a lot of work had, of course, been done, but more was required. In order to "provide for a regular connection with the Far East during, at least, five months in the year," technical improvements were necessary in the existing icebreaker fleet, as well as the construction of ships of a new type. This suggested program in all probability was the beginning of a second construction program. That it ever came to fruition is doubtful, but it is worthy of investigation in order to obtain some idea of the plans and schemes which were being drawn up and seriously examined.

Despite the fact that the first building program had included Diesel-electric icebreakers, of which type *Khabarov, Kirov* and *Kuibyshev* are reportedly in operation, but which are not mentioned in Kilesso's compilation, he presented his plan for new ships to include two types: a "superpowerful icebreaker" with either Diesel-electric or turbo-electric drive, and a Diesel driven freight-icebreaking transport of a displacement above 10,000-tons. The ambitions of his program are evident in the following table:

| | Icebreakers | Icebreaking Transports | | | |
|---|---|---|---|---|---|
| | | Diesel Cargo-Icebreaking | | | |
| | Superpowered (Planned) | *Stalin* Class | (Planned) Variant I | Variant II | *Dezhnev* Type |
| Length, meters ..... | 160.0 | 101.7 | 120.0 | 140.0 | 100.5 |
| Beam, meters ..... | 30.0 | 23.1 | 20.0 | 24.0 | 15.0 |
| Draft, meters ..... | 9.1 | 9.15 | 7.0 | 8.0 | 6.3 |
| Displacement, tons ... | about 24,000 | 10,900 | about 10,000 | | 6,530 |
| Horsepower ..... | 52,000 | 10,050 | 2 × 7,200 | | 2,500 |
| Type engines ..... | Diesel-elec. | Steam | Diesel with clutch | | Steam |
| No. propellers ..... | 4 | 3 | 2 | 2 | 1 |
| Speed, knots ..... | about 20 | 15.5 | about 18 | about 17 | 11.5-12 |
| Cruising radius, miles. | 10,000 | — | 6,000 | 7,500 | — |
| Net cargo capacity, tons ..... | Small hold for periodic cargo operations | No holds | 3,600 | 6,800 | about 2,300 |

This plan, as presented, is of interest for several reasons. In the first place, the draft of these new vessels was still within the limits prescribed by conditions along the coast of northern Russia. In the second place, the use, exclusively, of Diesel and Diesel-electric propulsion, could be taken as an indication of the fact that more stocks of oil had become available, or that the lack of economy of operating with coal was becoming more and more evident even in the latest types of icebreakers and steamers. Finally, there is found a sudden reticence on the part of Soviet writers with regard to the cruising radius of the new types. In view of the proposed cruising radius, it would appear that this radius, not less than the distance from Murmansk to Providence Bay, and possibly return, was far in excess of that of which the new vessels were capable.

The obvious question, of course, is, "Are vessels of this size feasible for Arctic operations?" Kilesso scorns all previous limitations as to size, making the point that so long as strength and engine power are adequate, size is unimportant. Basically, his contention was

that, whereas the relationship between power and displacement in the ordinary vessel is of the order of 0.2-0.5 to one, the icebreakers had a relationship from 1-1.5 and 2-2.5 to one, depending on the size, i.e., the smaller the icebreaker, the greater the relationship. Hence, he argued, the greater this relationship, the greater the mass of the icebreaker, and the greater the icebreaking strength. Greater strength was necessary because when the icebreakers had to work in ice above 1.5 to 2-meters in thickness, which condition was common even in the summer time along the Northern Sea Route, they were unable to move themselves, let alone convoy ships.

All the existing ships, it was felt, lacked adequate engine power and hull strength, and the only solution was to improve the hull lines, strengthen the hulls, increase tonnage, increase engine power, and increase the cruising radius.

This program was the result of a study of the collected statistical material on the world's icebreakers, those in use, those being built, and those being planned. Apparently the inescapable conclusion from this study was the table of characteristics as listed above.

When it is remembered that this was June 1940, little more than a year before the German invasion of Russia, it becomes fairly obvious that nothing was done along the lines proposed. Whether the entire program was scrapped is not, of course, known, but it is fairly certain that little or no construction took place during the war. Some contribution to the needs of the Soviet Union in the north was made by the lend-leasing of three of our own *Wind*-type icebreakers. Of the three, renamed *Kapitan Belusov, Severni Polius* and *Severni Veter,* the latter two are still in the hands of the Soviets, reported by them as being stuck "in solid jammed ice."[49] Whatever the excuse given for their non-return, the fact remains that icebreakers are of continuing need to the Soviets, who are pressing their explorations in the Arctic regions, and who have even gone so far as to point out that any claims staked out in the Antarctic regions cannot be recognized without Soviet participation in the final settlement of any such claims.

More recently, since the end of World War II, the only reported attempts to strengthen the fleet of icebreakers have been in the realm of repairs, such as the refit of *Lenin* in 1946-47, not in Russia, incidentally, but on the Mersey, and of *Litke* a year later in the same locality. Latvia, since the war again a part of Russia, as well as Lithuania and Estonia, contributed about five vessels to the fleet, and, as part of the war settlement, Finland was required to turn over icebreakers in her service.

Finally, Soviet sources have reported that the Red Sormova Works, on the Volga River, has been directed to construct river icebreakers, the first two to be delivered some time in 1950.[50]

Thus, all indications are that the Soviet Union plans to intensify activities along the Northern Sea Route and to attempt to maintain transportation on the rivers for as long a period as possible each year. The use of icebreakers has, in the past, enabled the Soviet Union to open up new sources of wealth and to exploit otherwise inaccessible areas. Obviously this process will continue. Yet, of even greater concern is the use of these icebreakers to convoy along the protected shoreline those supplies and men which would be needed in the event that drastic action in the Far East is decided upon by the Soviets.

It is hoped that this résumé will cast some light on the potentialities of the fleet of ships which work in the north, as well as on the possibilities for future expansion of the route to ease the burden on the always overloaded land transportation system from west to east.

[1] *Economic Review of the Soviet Union,* March 1, 1932, p. 110. Hereafter designated as *ERSU.*

[2] *Loc. cit.*

[3] *ERSU,* July 1, 1928, p. 238.

[4] While no direct statements concerning the use of the route for this purpose have been traced to Soviet authorities by the author, *La Revue Maritime,* November 1935, p. 693, had this to say: '. . . The importance of the new route lies not only in the cheapness of commercial transportation but also in the possibility of furnishing war materials to the Red Army in the Russian Orient, in case of an Asiatic conflict.' Translations of all foreign sources by the author.

[5] *La Revue Maritime,* May 1925, p. 706. The author was unable to find the original, Russian, source.

[6] *ERSU,* April 15, 1929, p. 152. There is, however, no indication of where these orders were placed, nor of the types ordered. Doubt exists as to any having actually been ordered at this time.

[7] F. I. Drigo, "Stroitelstvo ledokolnova flota," (Construction of the ice-breaker fleet), *Sovetskaya Arktika,* No. 9, September 1935, p. 8.

[8] *Loc. cit.*

[9] O. Shmidt, "Nashi zadachi v 1936 godu," (Our tasks in 1936), *Sovetskaya Arktika,* No. 3, March 1936, p. 34.

[10] Some construction was ordered abroad, and although reports called the few vessels thus ordered "icebreakers," the terminology was inaccurate. For example, *ERSU,* January 1933, pp. 22-23, mentioned a ship being built in the Burmeister-Wain yards, near Copenhagen, as an "icebreaker." Best evidence appears to indicate that this vessel was *Mossovet,* of 3000-gross tons, a coal burner with reciprocating engines, 325 feet long. A companion vessel, *Ural* or *Uralmash,* is believed to have been lost during the last war. Both vessels incorporated certain special design features to enable them to work in the ice, but their 2400 hp. and speed of 11 knots hardly puts them in the "icebreaker" category.

[11] *La Revue Maritime,* November 1934, p. 688, which claimed that "a super ice-breaker would be completed in the spring of 1935, in Leningrad, to have three times the power of *Krasin,*" was obviously in error.

[12] *Encyclopedia Britannica,* Vol. 20, 14th Edition, p. 516.

[13] Drigo, *op. cit.,* pp. 8-9. See also *La Revue Maritime,* May 1936, p. 698, which listed one *Sedov* type for hydrographic service, two steamers of the *Sevmorput* type, and two Diesel-electric type of 12,000 hp.

[14] See Jane's *Fighting Ships,* 1949-1950, p. 329, for details.

[15] Drigo, *op. cit.,* p. 9.

[16] N. A. Belousov and D. E. Tairov, "Stroim dizel-elektricheskie ledokoly," (We are building Diesel-electric icebreakers), *Sovetskaya Arktika,* No. 4, April 1936, p. 25.

[17] Details from *ibid.,* pp. 25-27.

[18] Jane's *Fighting Ships* indicates that this type has three shafts, two in the stern and one in the bow. This is at variance with the foregoing, and would appear to be in error, more particularly since Belousov and Tairov state, '. . . The bow propeller, unnecessary for an icebreaker cruising under Arctic conditions, is not being installed . . .' *Op. cit.,* p. 25.

[19] A sort of clubroom reserved for educational and/or recreational needs.

[20] *Drigo,* op. cit., p. 9.

[21] *ERSU,* March-April 1935, p. 101.

[22] *ERSU,* July 1, 1928, p. 238.

[23] *Ibid.*, April 1934, p. 102.

[24] N. A. Krysov, "O ledokolstroeny," (About icebreaker construction), *Sovetskaya Arktika*, No. 7, July 1936, pp. 94-97.

[25] Built in England by Armstrong in 1898. 8800-tons displacement, 9500-ihp.

[26] Accomplished, for the first time in the history of Arctic navigation, the northwest passage from Vladivostok to Murmansk in one navigation season. *Litke* departed Vladivostok June 28, 1934 and arrived Murmansk September 20, 1934, a voyage lasting 83 sailing days. *ERSU*, October 1934, p. 213.

[27] People's Commissariat for Heavy Industry. Drigo, *op. cit.*, p. 9.

[28] Since renamed *Mikoyan*.

[29] N. K. Matusevich and S. M. Koganov, "Novie sovetskie ledokoly," (The new Soviet icebreakers), *Sovetskaya Arktika*, No. 9, September 1937, p. 83. Jane's *Fighting Ships* indicates that only *Kaganovich* was built at Nikolaev, the other three at Leningrad. This would appear to be incorrect, particularly since confirmation of the building yards as listed appeared in *Przeglad Morski*, May 1936, cited in *La Revue Maritime*, November 1936, p. 695. See also *La Revue Maritime*, May 1936, p. 690.

[30] Drigo, *op. cit.*, p. 8.

[31] Dimensions are: No. 24, 240 x 124 mm; No. 30, 300 x 130 mm.

[32] Jane's *Fighting Ships* indicates that there is, in addition, a Diesel-electric installation for cruising speeds. There is no evidence of this in Matusevich and Koganov, but it is, of course, conceivable that such an installation may have been made at a later date.

[32A] A. Yanvarsky, "Novie Ledokoly I. *Stalin* i L. *Kaganovich*," (The new icebreakers *J. Stalin* and *L. Kaganovich*), *Sovetskaya Arktika*, No. 7, July 1938, p. 18.

[33] *Izolyator*, which could be interpreted to mean a "solitary confinement cell," or brig, but if Soviet propaganda is to be believed, it is hardly conceivable that the Soviet sailor would ever have to be placed in such a "bourgoise" contrivance as a brig.

[34] Matusevich and Koganov, *op. cit.*, p. 84.

[35] Belousov and Tairov, *op. cit.*, p. 27.

[36] Matusevich and Koganov, *op. cit.*, p. 83.

[37] Drigo, *op. cit.*, p. 10.

[38] Drigo, *op. cit.*, p. 10.

[39] The organization charged with the planning of ship construction.

[40] Belousov and Tairov, *op. cit.*, p. 27.

[41] G. Guari, "Nashe kapitalnoe stroitelstvo," (Our capital construction), *Sovetskaya Arktika*, No. 1, January 1936, pp. 109-110.

[42] N. M. Yanson, "Plan raboty Glavsevmorput v 1937 godu," (Plan of the work of Glavsevmorput in 1937), *Sovetskaya Arktika*, No. 2, February 1937, p. 19.

[43] N. A. Belousov, "Byt gotovym k navigatsii 1937 goda," (To be ready for navigation in 1937), *Sovetskaya Arktika*, No. 3, March 1937, pp. 24 ff.

[44] Yanson, *op. cit.*, p. 19.

[45] Belousov, *op. cit.*, pp. 24 ff.

[46] *La Revue Maritime*, November 1937, p. 670 and *ibid.*, May 1939, p. 699.

[47] A. Kilesso, "O novykh tipakh arkticheskikh sudov," (Concerning new types of Arctic ships), *Sovetskaya Arktika*, No. 6, June 1940, p. 19.

[48] The discussion which follows is drawn from *ibid.*, pp. 17 ff.

[49] *N. Y. Times*, June 1, 1950, p. 20.

[50] *U.S.S.R. Information Bulletin*, Washington, D. C., February 10, 1950, p. 97.

# THE DISTINGUISHING CHARACTERISTICS OF WATER-FORMED DEPOSITS

FRANK E. CLARKE

THE AUTHOR

graduated from Western Maryland College in 1935 with A.B. degrees in chemistry and education. He studied advanced physical chemistry for one year at the University of Maryland and taught chemistry for four years before entering the Boiler Water Section of the EES Chemical Laboratory in March 1941. He became head of the Boiler Water Section in 1942 and in 1946 became head of the Chemical and physical branch of the EES Chemical Engineering Laboratory which absorbed the Water Section. He was chairman of ASTM Committee D19's section on sampling of water deposits during the preparation of standard definitions and methods for such materials. He currently is Chairman of Committee D-19's subcommittee on analysis and testing of water and water-formed deposits. His best known analytical contributions are the ASTM standard on determination of carbon dioxide in water and a recently published method for determination of chloride in water.

Water-formed deposits can be logically classified as scales, sludges, corrosion products, high temperature oxides and biological deposits, depending on their methods of formation. Unfortunately there is a decided lack of consistency in the use of these terms by operating engineers. This paper discusses the fundamental characteristics of deposits in accordance with definitions of the American Society for Testing Materials. It is aimed at promoting better understanding of deposits and more uniform use of terms related to them.

## SCALE

The term "scale" is used frequently and somewhat indiscriminately in describing water-formed deposits. Scale is best defined as a deposit formed from the water, directly in place upon a confining surface. True scales are crystalline and dense and frequently consist of columnar crystals growing at right angles to the confining surfaces. They generally are hard and adherent, so that they retain their shapes when removed by mechanical means. However, it is possible for true scales to be soft and non-adherent. The method of

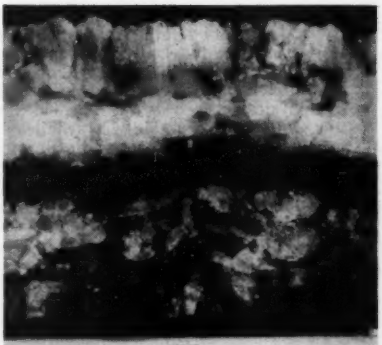
*Table 1*

*Composition of Scales in Figures 1 and 2*

| *Constituent* | *Per Cent* *Hard Scale* | *Soft Scale* |
|---|---|---|
| Calcium Sulfate, $CaSO_4$ | 20.05 | 1.11 |
| Calcium Silicate, $CaSiO_3$ | 23.00 | — |
| Calcium Hydroxide, $Ca(OH)_2$ | — | 95.50 |
| Calcium Phosphate, $Ca_3(PO_4)_2$ | 21.26 | 0.70 |
| Magnesium Phosphate, $Mg_3(PO_4)_2$ | 7.65 | 1.13 |
| Organic Matter | 5.22 | 0.60 |
| Silica, $SiO_2$ | 1.19 | 0.60 |
| Iron Oxide, $Fe_2O_3$ | 15.60 | 0.80 |
| Copper Oxide, CuO | 2.13 | — |
| Lead Oxide, $PbO_2$ | 0.10 | — |
| Zinc Oxide, ZnO | 0.90 | — |
| Soluble Sodium Compounds | Remainder | — |

formation and the resulting internal structure determine whether or not a deposit is scale. Figures 1 and 2 show microstructures of a hard adherent scale and a soft non-adherent scale, respectively. Columnar crystals can be seen in both. The corresponding analyses in Table I show that the hard scale was primarily a mixture of calcium silicate and calcium sulfate. The soft scale was the relatively soluble crystalline product calcium hydroxide (hydrated lime).

Scale deposits result from the presence in water of dissolved minerals which will crystallize on confining surfaces with increase in temperature, increase in concentration (as by evaporation) or change in pH (acidity) of the water. The carbonates, silicates and sulfates of calcium, and the carbonate of magnesium are principle offenders. More soluble compounds, such as calcium and magnesium hydroxides, will deposit under certain conditions. Troublesome minerals are present in all natural waters, and to a considerably lesser degree in distillates therefrom. The sea water used aboard Naval vessels for distillation of boiler feedwater, contains an abundance



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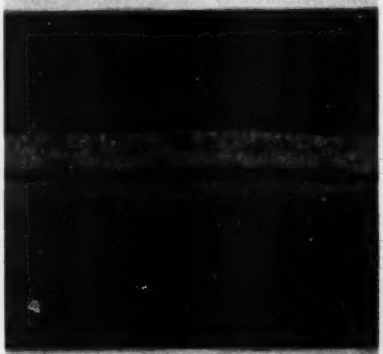

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Figure 1 - Hard Adherent Scale

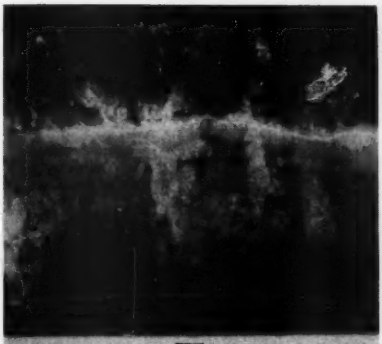

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Figure 2 - Soft Non-adherent Scale

of scale forming calcium, magnesium, bicarbonate and sulfate ions in addition to its major, non-scaling ions sodium and chloride. When evaporated it tends to develop crystalline scales of calcium carbonate on the tubes of low pressure evaporators. In high pressure evaporators and boilers it tends to deposit mixtures of calcium carbonate, magnesium hydroxide and calcium sulfate. Chemical treatments like Navy Boiler Compound, are aimed at counteracting the scale forming tendencies of small quantities of dissolved solids which carry over with distillate or leak into condensate. These treatments generally provide phosphate ion to convert calcium and magnesium ions to non-adherent, phosphate sludges, and alkalinity to minimize corrosion.

It is important to note that the ingredients of Navy Boiler Compound are proportioned to yield proper conditions with sea water distillate only. The simultaneous removal of scale-forming ions and adjustment of alkalinity generally cannot be obtained with it if the feedwater contains contaminants other than sea salt. The use of alternate feedwaters has resulted in instances of serious scaling in Naval boilers. The scales shown in Figures 1 and 2 were caused by shore water and lime from cemented tanks, respectively.

Scales are objectionable in heat transfer equipment because they insulate the metal surfaces, reduce efficiency and, in serious cases, cause heat blistering and failure. Figure 3 shows a ruptured heat blister caused by the boiler scale of Figure 2. The undesirability of scale is increased by the fact that it is extremely difficult to remove by mechanical means, particularly from the insides of small tubes. At best, it is only slowly soluble in properly treated boiler water. The more persistent varieties, such as silicate scales, can be removed only by chemical cleaning.

Figure 3 - Scale Damaged 2" Boiler Tube

## SLUDGE

Sludge is a sedimentary deposit. It results from the settling out of suspended matter on confining surfaces. Accordingly it includes scale and corrosion products which have broken loose from the confining surfaces and insoluble reaction products of feedwater treating chemicals with scale forming constitutents of the feedwater. It also includes general debris from outside sources, like lubricating oil and mud. Because of the method of formation, the microstructures of sludge deposits vary from powdery films to conglomerates of sundry particles. They can be identified by the absence of uniform, internal structure. Sludge masses generally are soft and non-adherent, so that they will not retain their shapes when removed mechanically. On the other hand, it is possible for sludge to bake on heat transfer surfaces and to become hard and adherent. The presence of adhesives, like oil, grease, or paint may cause sludge to roll up into sludge balls, or congeal into tar-like masses. Plates 4 and 5 show the microstructures of soft non-adherent sludge and hard adherent sludge, respectively. Plate 6 shows sludge balls taken from the mud-drum of a Naval boiler. The concentric structure can be seen in the broken ball. These balls resulted from contamination of the feedwater with lubricating oil from a reciprocating engine. The corresponding analyses for these sludges are given in Table 2.

A limited amount of soft, non-adherent sludge is unavoidable on the water-sides of boilers. It includes small quantities of metal oxides from gradual corrosion and erosion of metal surfaces in the feedwater and boiler systems and insoluble phosphates from reaction of metal ions with feedwater treatment chemicals. This sludge generally remains suspended during operating periods and deposits in the form shown in Figure 4 during idle periods. Excessive accumulation of sludge is prevented by regularly blowing to waste a small portion of the boiler water. The residual sludge films are removed during overhaul periods by water washing and

*Table 2*

*Composition of Sludges in Figures 4, 5 and 6*

| | Percent | | |
|---|---|---|---|
| *Constituent* | *Soft Sludge* | *Hard Sludge* | *Sludge Balls* |
| Calcium Phosphate, $Ca_3(PO_4)_2$ | 78.29 | 1.31 | — |
| Magnesium Phosphate, $Mg_3(PO_4)_2$ | 8.55 | — | 6.05 |
| Calcium Carbonate, $CaCO_3$ | — | 44.60 | — |
| Magnesium Hydroxide, $Mg(OH)_2$ | — | 20.50 | — |
| Oil | — | — | 19.30 |
| Solid Organic Matter | 3.51 | — | 14.85 |
| Calcium Sulfate, $CaSO_4$ | 1.39 | 8.30 | — |
| Silica, $SiO_2$ | 0.23 | 7.38 | 0.37 |
| Iron Oxide, $Fe_2O_3$ | 7.00 | 18.20 | 7.13 |
| Iron Oxide, $Fe_3O_4$ | — | — | 27.80 |
| Copper Oxide, CuO | — | — | 18.55 |
| Lead Oxide, $PbO_2$ | — | — | 0.22 |
| Zinc Oxide, ZnO | — | — | 2.80 |
| Nickel Oxide, NiO | — | — | 1.18 |
| Tin Oxide, $SnO_2$ | — | — | 0.60 |
| Copper, Cu | — | — | 1.00 |

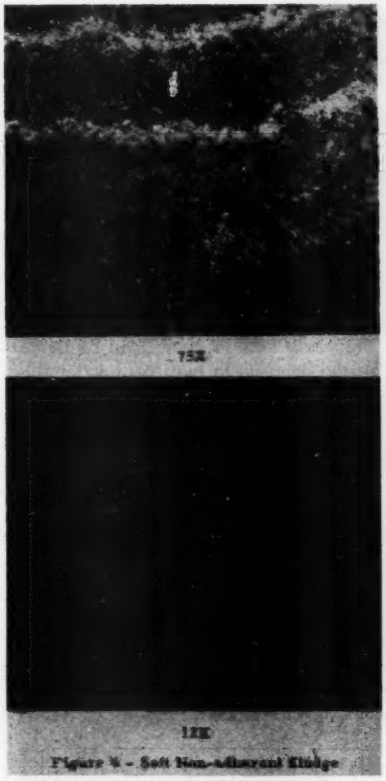

Figure 4 - Soft Non-adherent Sludge

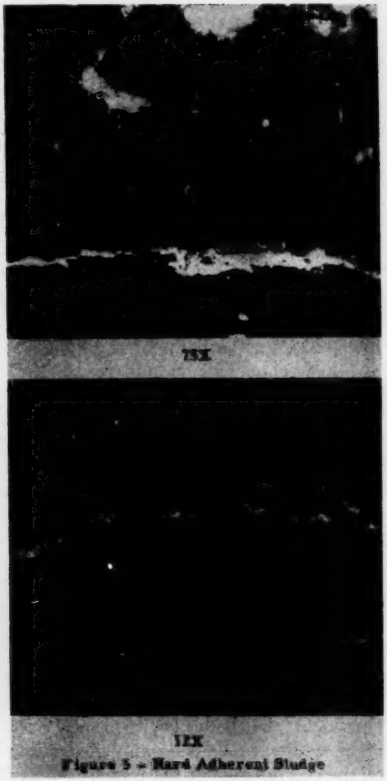

Figure 5 - Hard Adherent Sludge

brushing. If blowdown is inadequate to cope with the quantity of sludge produced, sludge fouling of the heat transfer surfaces will occur during operating periods and baked sludge will result. Similar fouling will occur if periodic cleaning of the water-sides is ineffective or too infrequent. Baked sludge is extremely difficult to remove and has the same effect as scale. Figure 7 shows a boiler tube which failed from baked sludge and heat blistering.

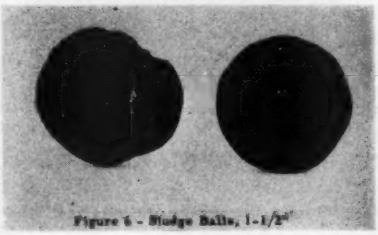
Figure 6 - Sludge Balls, 1-1/2"

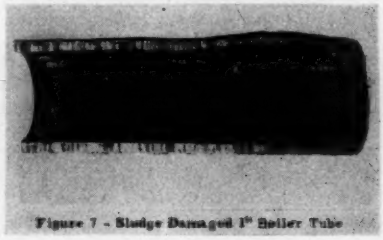
Figure 7 - Sludge Damaged 1" Boiler Tube

## CORROSION PRODUCTS

Corrosion products result from chemical reaction between the water and its confining metal surfaces. These reactions generally convert a portion of the metal to insoluble products such as iron rust. The thin iron oxide film which normally is present on the water-side of a healthy boiler is an example. Oddly enough, this has a beneficial effect in retarding serious corrosion. It is possible for the corroded area to be clean and for the corrosion products to deposit a great distance from the point of reaction. For example, copper, zinc and nickel corrosion products formed in feedwater systems frequently are deposited as sludge in related boilers. Some corrosion products are relatively soluble. These may remain dissolved in the water and later crystallize as scale during evaporation, or react with water treatment chemicals to form sludges. Ferrous chloride is a typical soluble corrosion product.

It is to be emphasized that iron rust is only one of many corrosion products. Virtually all of the metals used to handle water will corrode to some extent, and the deposits resulting from them will vary considerably depending on the composition of the water. A water high in carbon dioxide content will develop metal carbonates on copper and nickel alloys. Acidic water high in chloride ion content will produce ferrous chloride. Alkaline water will react with zinc to form zinc hydroxide. Iron oxide (rust) is the most prevalent corrosion product in Naval power plants. The oxides of copper, nickel, lead and zinc also occur in appreciable quantities.

From the above it can be seen that corrosion products resemble scales in that they form in place. They differ from scales in that they involve attack on the metal. Corrosion products may be crystalline, however, their deposits rarely have a definite structural pattern. In this sense, they can be considered a specific category of sludges. Figure 8 shows an iron oxide scab in a dissolved oxygen pit of a boiler tube. This is the most localized type of corrosion deposit. Figures 9 and 10 show iron oxide corrosion deposits in two fresh water lines. The first specimen contains serious corrosion which probably was responsible for the deposit. The second specimen is uncorroded as though the deposit washed into it from an outside source. Deposits of the type shown in these figures have the same objections as scale and sludge relative to reduction of heat transfer.

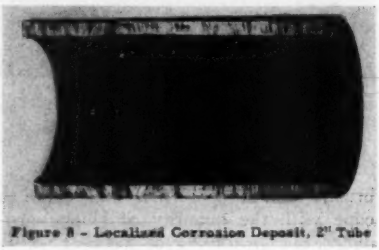

Figure 8 - Localized Corrosion Deposit, 2" Tube

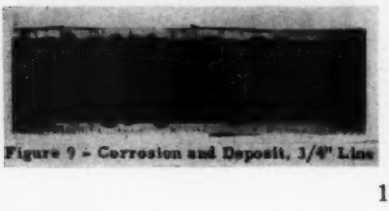

Figure 9 - Corrosion and Deposit, 3/4" Line

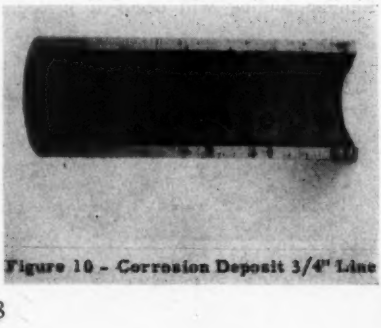

Figure 10 - Corrosion Deposit 3/4" Line

## WATER-FORMED DEPOSITS

### HIGH TEMPERATURE OXIDES

High temperature oxides result from reaction of steel with high temperature steam. They are relatively thin, compact, shiny films of mixed iron oxides, which contain FeO, $Fe_3O_4$ and $Fe_2O_3$. The ratios of the compounds are determined primarily by the temperatures attained. Such oxide films frequently are referred to as mill scales, because similar films form during the hot rolling of steel. Actually the deposits resemble corrosion products more closely than scale, since they involve reaction of a metal with its environment. They are more uniform than corrosion products and do not involve the action of liquid water.

A thin film of high temperature oxide can be beneficial in retarding corrosion, as on the steam side of superheater tubes. On the other hand, the presence of high temperature oxide in low temperature, steam generating tubes indicates that serious overheat and permanent damage to the metal has occurred. Repeated formation and alkali solution of high temperature oxide in hot spots of fire-row, boiler tubes has been known to cause gradual grooving of the tube walls and serious iron oxide sludging of other parts of the boiler. Compact high temperature oxides have little effect on heat transfer, and become important only if they signify abnormal temperatures or lead to tube wasting and sludging as discussed above. Overheat from faulty circulation is the most common cause of serious high temperature oxidation.

### BIOLOGICAL DEPOSITS

Biological deposits consist of the bodies of water-born organisms or the products of their life processes. Such deposits sometime occur on cooling water sides of condensers and other types of heat exchangers. They include marine life ranging from algae in fresh water to barnacles in sea-water. Their principal effects are obstruction of flow and reduction of heat transfer. In certain instances they cause serious corrosion. They are controlled by chlorination, high temperature washing, copper ion poisoning and other special treatments.

### IMPORTANCE OF DEPOSIT CLASSIFICATION

The operating engineer cannot be expected to accurately classify the deposits discussed above. However, when supplied with representative samples, a laboratory experienced in water technology generally can reconstruct the condition which led to deposition. The photomicrograph in Figure 11, of a boiler deposit serves to illustrate this possibility. Layer (a) is a compact film of high temperature iron oxide. It is overlaid with a thick mixture of magnesium phosphate sludge, calcium hydroxide scale and metal oxide corrosion products, (b), which in turn is covered with a heavy layer of calcium sulfate scale, (c). The presence of calcium

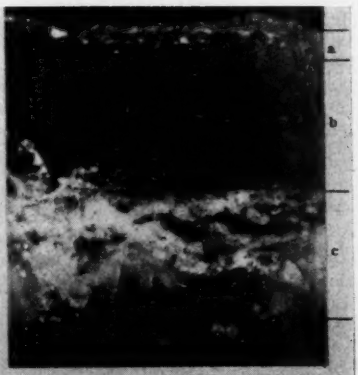


Figure 11 - Microstructure of Stratified Deposit

hydroxide scale in the intermediate layer, (b) shows that the boiler water was contaminated with lime (from a cemented feedwater tank) and that all of the scale combating phosphate ion had been consumed. The absence of phosphate allowed the formation of calcium sulfate scale from the small quantities of calcium and sulfate ions always present in Naval boiler feedwater. The iron oxide film, (a), did not contribute to the failure but resulted from overheat, brought about by scale insulation and overheat of the tube.

## IMPORTANCE OF SAMPLING

To yield information of the above type, deposits must be removed and submitted to the laboratory as nearly as possible in their original forms. If practicable, a portion of the metal surface with the deposit in place should be cut away without removing the deposit. This generally can be done with boiler tubes, evaporator tubes, condenser tubes, etc. When metal cutting is not practicable, deposits can be removed from the insides of tubes by brushing or scraping and from the outsides of tubes by thermal shock. The latter method is frequently used in descaling evaporators. Samples obtained by brushing and scraping are relatively poor for investigational purposes and serve to determine chemical composition only. Deposits can be removed from tank walls and other large surfaces by striking them with a hammer. Soft deposits can best be removed from large surfaces by scraping with a strong sharp instrument capable of completely separating the deposit, with or without a portion of the metal surface. Whatever the method of sampling, it is important that the deposit be collected and forwarded in a clean container. Complete information should be provided concerning the exact spot from which the sample was removed, the method used in its removal, and any pertinent information regarding conditions which existed in its environment at the time of removal.

## CONCLUSIONS

The multitude of water-side deposits encountered in Naval service can be broken down into the five fundamental types described in this paper. An understanding of water technology makes it possible to detect and identify scale, corrosion products, high temperature oxide, etc. even when they are removed from their places of formation and thoroughly mixed with deposits of other types. The care exercised in sampling the deposit and providing background information on it, markedly affects its value. Close cooperation between the operating engineer and the technical laboratory is essential to accurate diagnosis and correction of water-side conditions which lead to deposits.

# ANOTHER NEW HIGH-PRECISION, UNIVERSAL-FREQUENCY COMPUTER COMPONENT

DONALD HERR, HONORARY MEMBER
JOHN LOY AND NORMAN BLUMENSTOCK

THE AUTHORS

The biographies of MESSRS. HERR and BLUMENSTOCK already appear in the May 1950 issue of the *Journal*. MR. LOY, laboratory assistant to MR. HERR, is Master Instrument Machinist, Reeves Instrument Corp., New York City.

In a previous paper a new induction resolver computer component, with functional and angular accuracy, internal "noise" characteristics and universal frequency operation, superior to all known types, was described.[1] Based upon the theoretical and design considerations referenced in a companion paper,[2] another new high-precision, universal-frequency computer component, a linear induction potentiometer of superior accuracy, internal noise and useful rotational angle, has been developed and is now in mass production.

This new induction potentiometer, first demonstrated for the profession at the March 1950 Institute of Radio Engineers National Technical Session and Convention, New York City, intrinsically develops the isosceles triangular amplitude function of angle of shaft rotation depicted in Figure 1a. It may be used at an a.c. carrier frequency of less than 60 cps to greater than 1 kcps, in conjunction with its appropriate booster-amplifier. Unlike all other known types of a.c. induction potentiometers, it is not only a continuous rotation device but also develops the idealized output amplitude function of shaft angle depicted in Figure 1a over the *entire* 360 degrees of shaft rotation, with an accuracy of $\pm 0.1$ of 1 percent and noise content at a maximum coupling (time harmonic) and at minimum coupling (carrier frequency quadrature) of less than 0.1 of 1 percent of input excitation, over the entire carrier frequency range, when used with the appropriate compensating booster-amplifier.

The induction potentiometer weighs approximately one pound and provides stepless, non-granular, non-open-circuiting control of precision follow-up servomechanisms heretofore impossible with wire wound potentiometers.

In Figure 1b are depicted various alternative output voltage amplitude-functions of shaft angle of rotation attainable with the new induction potentiometer by use of an added miniaturized, self-contained switching arrangement and

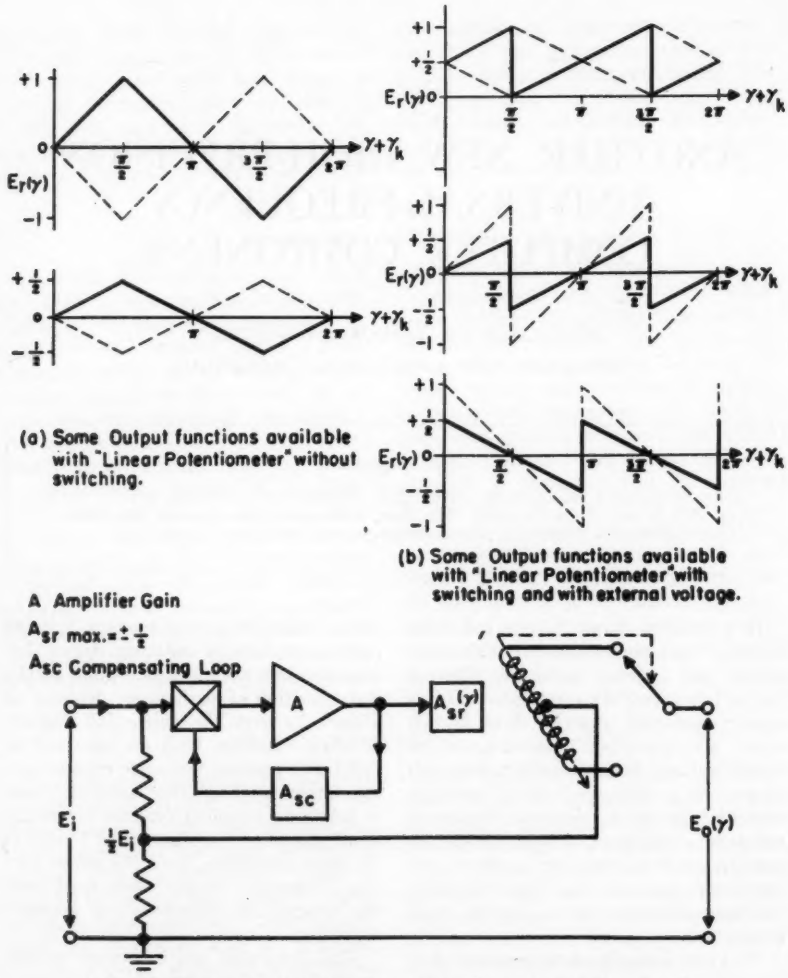


FIG. 1—The Induction Linear Potentiometer.

circuitry, such as shown in Figure 1c.

The functions depicted in Figure 1b are essentially "two speed." By two-to-one gearing the induction potentiometer becomes a "one-speed" device with, of course, double the errors present in the potentiometer itself. For example, the abrupt discontinuity from a positive maximum to zero output occuring each 180° of shaft rotation actually done in two discrete steps, the first discontinuity being from positive maximum output to

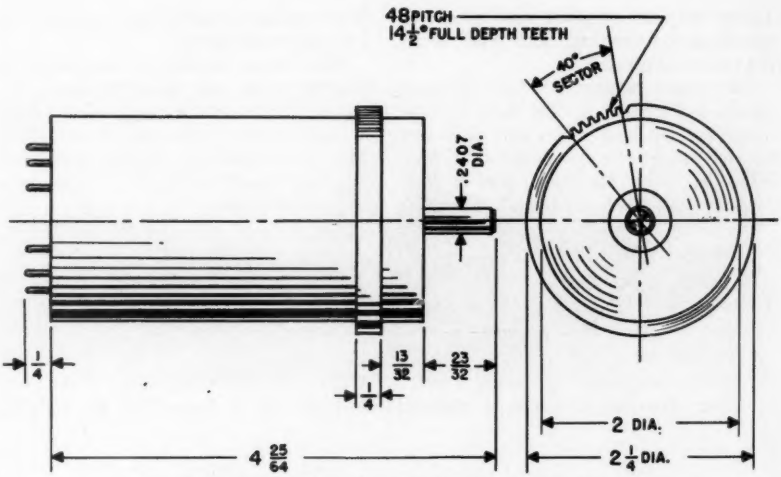


FIG. 2—External Dimensions of Induction Potentiometer.

one-half this value; the second discontinuity being from the half-value to zero *after* constant half-value output for a shaft angle-of-rotation of 8 minutes of arc. But at no time is there an *open-circuited* output such as in conventional wire-wound potentiometers nor is there the "granular" step-wise type of output variation with angle as is encountered in wire-wound linear potentiometers.

In Figure 2 are given the external dimensions of this high-precision, universal-frequency linear induction potentiometer. The terminals are pin-type and the rotor winding (or windings) is the output side of the device. The frictional torque and inertia characteristics of the linear induction potentiometer are the same as those already given for the high-precision, universal-frequency induction resolver.[1] Temperature compensation may be effected in the compensating booster-amplifier or by use of an internally wound compensating winding. The former type of induction potentiometer is designated as the "P-4000"; the latter as the "P-4001."

FIG. 3—Induction Potentiometers and Booster Amplifiers.

Either may be supplied with single or double-ended shafting, both types being depicted in Figure 3.

The upper booster amplifier-compensator of Figure 3 is that used for the lower carrier frequencies and the lower booster amplifier-compensator of Figure 3 is that used for the higher carrier frequencies (400 to 1000 cps). The relative amplifier weights are 5 pounds and 1 pound, respectively.

This device should be considered as another in the new family of high- precision, universal-frequency electromagnetic-induction computer components. The production and testing procedure for it are substantially the same as those already described.[1]

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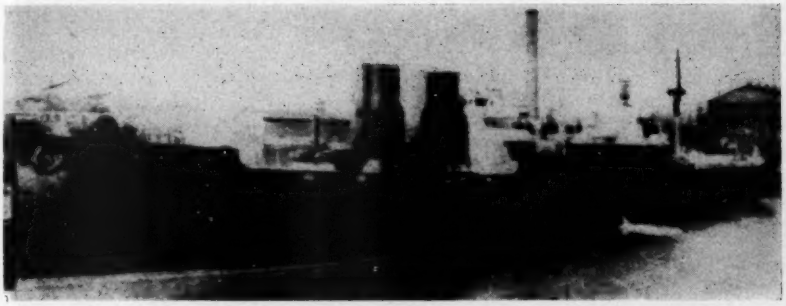


Figure 1.—*Jacona.*

# MOBILE POWER PLANTS FOR EMERGENCY MILITARY OR CIVIL DEFENSE

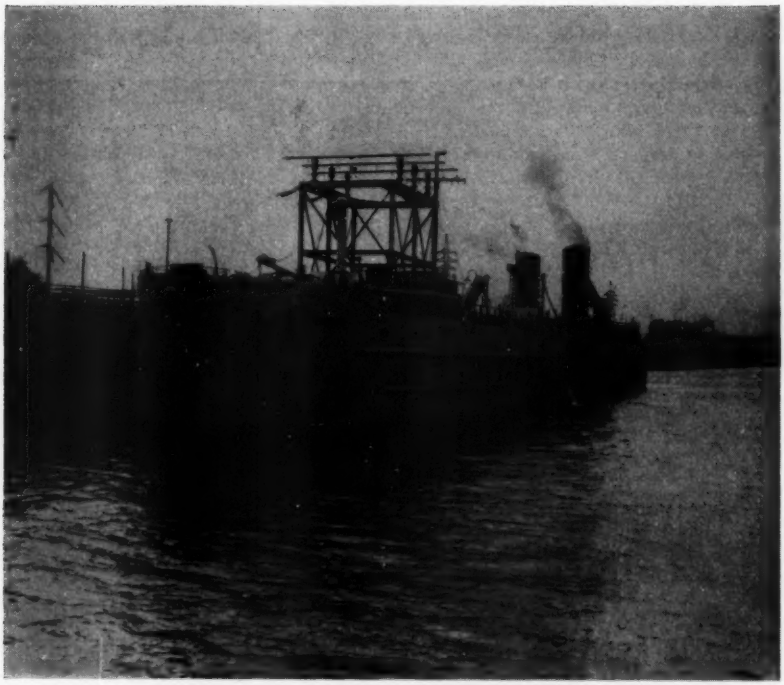
CAPTAIN CARL J. LAMB, USNR (INACTIVE)

THE AUTHOR

who spent three years at the Naval Academy and was commissioned in the Naval Reserve in June, 1917, has contributed four previous articles to the JOURNAL. In addition to a long period of time in the central station and marine departments of the Westinghouse Electric Corporation, he has spent many years at sea in the Navy and Merchant Marine, and holds unlimited Marine Chief Engineers License, steam and motor, in addition to professional Engineer licenses for the states of Connecticut and Indiana. At the present time Captain LAMB is practicing engineering at Tampa, Florida.

At the conclusion of World War II it was widely expected that our possession of the Atom Bomb, together with the formation of the United Nations and an assumed world-wide desire for peace, would result in the "One World" envisioned by Franklin D. Roosevelt and Wendell Willkie. Very soon after the war, however, it became evident that instead of one world which desired peace and prosperity, there are two, one of which, Russian led and controlled, desires to overcome and conquer our Western world, which includes the United States.

Time has demonstrated that there are



Courtesy Gielow Incorporated, Naval Architects, New York.

Figure 2.—*Seapower,* Plancor 525, Power Plant "D."

only two great powers existing today, the United States and Russia. It has now become too evident that the dominant Russian policy is to destroy the United States, by any or all means, if possible.

As the result of weapons and techniques developed during and since World War II, it is now possible for an enemy to attack our great coastal cities and concentrated industrial manufacturing centers by air, and also by rocket launching submarines from the sea.

In considering such a possible situation, the writer felt that destruction of power generating facilities in the Naval, Military and Air bases or industrial manufacturing centers, on or adjacent to our coasts, would be disastrous, whether brought about by air attack, submarine launched missiles, or sabotage. Based upon a 20,000 KW, non-propelled floating power plant, *Jacona,* designed before World War II, for a New England public utility, and taken over by the Army during World War II, and upon 4 - 30,000 KW non-propelled (towed) floating power plants, recommended by the War Production Board, and designed for the Defense Plant Corporation by Gielow Incorporated during World War II for domestic use,[1] it

seemed that there would be both need and justification for such plants in the future. In an article, "Engineers Will Mold the Future," published in November 1947 issue of *Scientific American*, the idea was mentioned, and illustrated by a photograph of the floating power plant *Seapower*.

At the same time, in cooperation with Gielow Incorporated, a study was made as to the economic and military practicability of self-propelled floating power houses to be constructed and held in reserve for either military or civil defense emergencies. Careful study indicated that a complete 30,000 KW power plant could be installed in a Liberty ship hull, together with evaporators of 80,000 gallons fresh water daily capacity, of air compressors of moderate capacity and fuel for three months.

Accordingly the writer suggested to the Navy Department consideration of ten or more such self-propelled floating power plants, to be constructed in "Liberty" ship hulls, which were surplus and obsolescent as profitable merchant ships. The salient general details, and basic reasoning were as follows:

1. Use existing Liberty ships which were greatly in surplus of existing commercial requirements.

*Reasons:* Save steel, save time, save construction costs. Also, while slow and inefficient the power plant boilers of a Liberty, which would only be required for propulsion when propelling the vessel to its emergency destination, could be used to furnish steam to Naval or commercial shipyard dock steam lines, to operate evaporators at sea and to light off and warm up the main turbine generators upon nearing the emergency destination. This use of the existing boilers eliminates the need, weight and cost required for Diesel generators as employed in the four non-self propelled power plants built during the war.

2. Install 1 - 30,000 KW; 2 - 15,000 KW; or 3 - 10,000 KW (80% PF) central station type turbine generators, together with necessary condensers and auxiliaries of marine type. Install marine type boilers, boiler auxiliaries and combustion equipment. Have 200 psi steam connection from ship's boilers to power plant main and auxiliary steam lines.

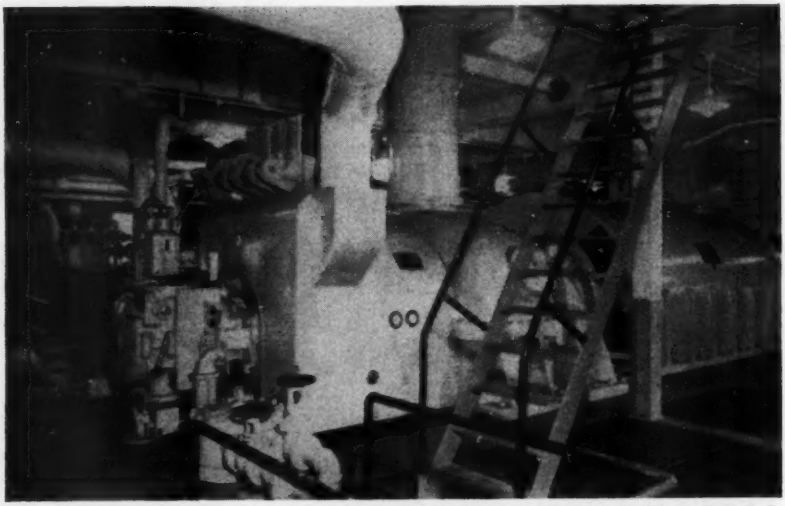
*Reasons:* The use of the latest and most modern type central station type turbine generators will save time and money. On the other hand, the use of Naval type boilers, condensers and auxiliaries is necessary to save weight and conserve space, in order to provide for a large fuel supply. Use of 10,000 KW units allows procurement from six manufacturers.

3. Install a main transformer provided with taps for 132, 126, 120, 112, 109, 69 and 63 kilovolts, and an auxiliary turbine generator, capable of being operated from either low pressure ship's boilers or high pressure power plant boilers.

*Reasons:* To be able to supply current at practically any desired locality, at a wide variety of voltages, and at 50 cycle when necessary.

4. Install a triple or quadruple effect evaporator plant, 80,000 gallons per day capacity, fitted with U.S.S. *Indianapolis* starch treatment plant.[2]

*Reasons:* A small evaporator would be required in any event, to supply boiler make-up feed water for both ship propulsion, and power plant steam generators, and for potable water for the operating crew. By providing storage for 80,000 gallons of fresh water and evaporators capable of distilling 80,000 gallons per day, the ship could supply emergency fresh water to other ships, hospitals, communities, military bases, etc., in case fresh water supply had been inter-



Courtesy Gielow Incorporated, Naval Architects, New York.

Figure 3.—30,000 KW G. E. Turbine Generator installed in *Seapower*.

rupted or contaminated by enemy attack.

5. Install several turbine or motor driven, cruiser type, high speed, 165 psi air compressors.

*Reasons:* To supply air to dock lines of Naval and merchant shipyards which had been subject to enemy direct attack or sabotage. If it were necessary to move the power plant to any given emergency location to generate power, it is probable that shipyard air compressor plants might also be out of commission.

6. Provide for manning the self-propelled floating power houses by specially trained Naval Reserve personnel.

*Reasons:* Since the proposed mobile power houses are to be self-propelled, and to have the propulsion boilers available for lighting off, warming up and certain auxiliary and emergency functions, the responsibility for both plants will be taken by one Chief Engineer. Naval and properly trained Naval Reserve personnel are more familiar with propulsion machinery, Naval type boilers, auxiliaries and evaporators than are Merchant Marine or power plant personnel. Such vessels should be protected against air and submarine attack by proper weapons, and well drilled as to damage control, which requires well disciplined men.

7. Provide for mooring such emergency, self-propelled power plants in small, non-strategic out-of-the-way anchorages, harbors or rivers, with ship keepers aboard and the trained reserve crew members designated, so that in the event of emergency or war they may be mobilized quickly.

*Reasons:* Such emergency floating power houses would be less subject to initial attack if moored in non-strategic, little known or hard to reach locations.

Now that we know what the future may bring, and are prepared to face realities, it behooves us as a nation to plan for the unwelcome war which may be waged against us. The non-self-propelled floating power houses designed and developed by Gielow Incorporated and operated by the U. S. Army amply justified their existence, at home and abroad, during the last war. If they were available for the next war, they are not suitable for the requirements which that war may impose, and the conversion of self-propelled Liberty ships to mobile seagoing emergency power houses may be accomplished more rapidly, at lower cost and without appreciable expenditure of vitally important steel.

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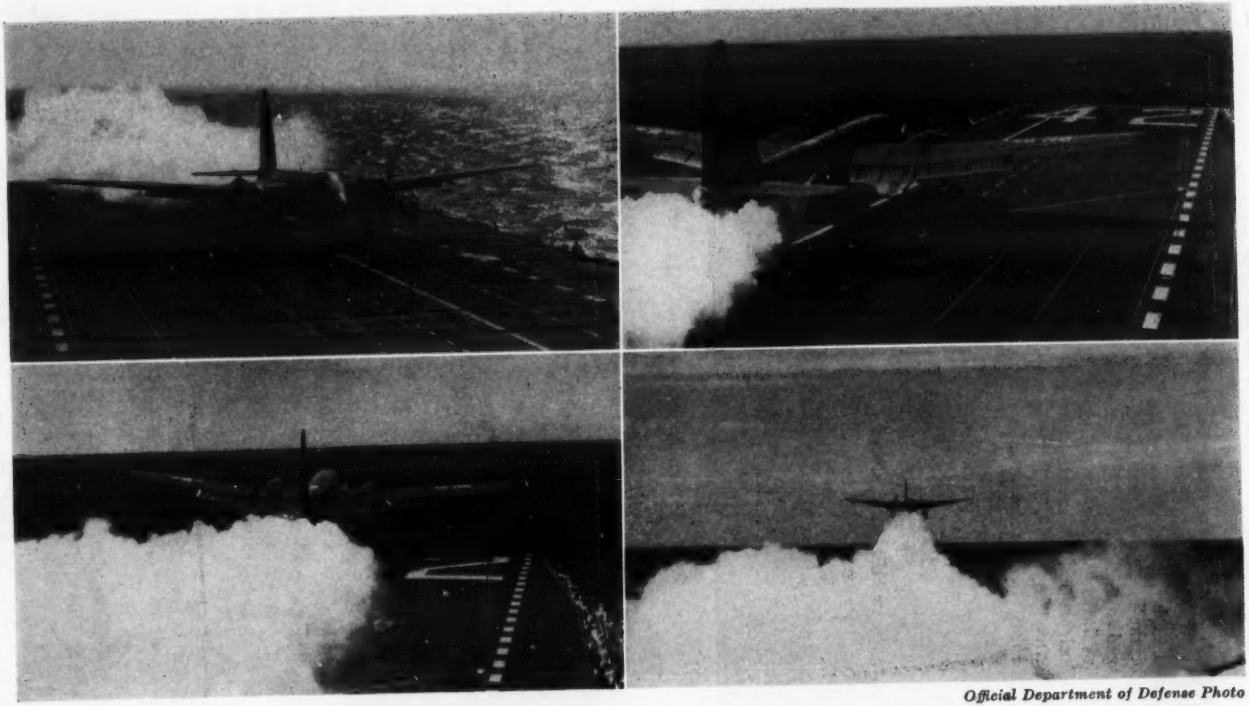

*Official Department of Defense Photo*

Navy Neptune Takes Off From Aircraft Carrier

Navy Neptune Takes Off From Aircraft Carrier

# PART TWO

## REPRINTED ARTICLES

The articles contained in this Part Two represent those which, in the opinion of the editorial staff, are the most valuable which have been gleaned from recent issues of contemporary publications.

This material was formerly published under the heading "NOTES". It has been given somewhat more prominence and made more readable to enhance its value. The editors' purpose here is to provide a convenient repository to readers of the JOURNAL, for articles originally published elsewhere which contribute to the purpose of the Society: to further the advancement of naval engineering.

# SPECIAL NOTICE

THE ANNUAL BANQUET OF THE SOCIETY

WILL BE HELD AT

THE STATLER HOTEL

IN WASHINGTON, D. C.

ON

**FRIDAY, 27 APRIL 1951**

THE PRESIDENT OF THE SOCIETY WILL PRESIDE

**REAR ADMIRAL W. D. LEGGETT, JR., U.S.N.**

DEPUTY CHIEF OF THE BUREAU OF SHIPS

WILL ACT AS TOASTMASTER

THE PRINCIPAL SPEAKER

HAS NOT YET BEEN SELECTED

# PROSPECTS OF GAS TURBINES IN NAVAL APPLICATIONS

ACKNOWLEDGMENT

*Mechanical Engineering*, September, 1950, contained this article by Commander R. T. SIMPSON and W. T. SAWYER, USN. The article was presented at the Spring Meeting of the ASME, 1950.

## HISTORICAL

Hero, the Alexandrian is credited with first conceiving the principle of the gas turbine in 130 B.C. The first patent was issued to the Englishman, John Barber, in 1791. Despite these very early origins, real progress was not realized until made possible by advances in the metallurgical and aerodynamic sciences early in the twentieth century. By 1930, however, very positive progress was on record, including the turbosupercharger developed in this country by Dr. Sanford Moss. That year marked the appearance on the drafting boards of Whittle's first aircraft gas-turbojet engine and ushered in the really modern era of extremely rapid development. A full chronology of gas-turbine development during the long period so briefly referred to may be found in the work of R. T. Sawyer (1), Moss (2), and others (3, 4, 5, 6).

During the 1930's important advances were made by the Swiss firms of Brown-Boveri, Escher Wyss, and Sulzer in their programs of locomotive and land power station gas-turbine development. These events were reported comprehensively to the Navy Department's Bureau of Engineering by Lieutenant Commander Warren Noble, USNR, in 1938. His estimate of the situation was so startingly enthusiastic that the Department almost immediately requested an investigation by a committee of the National Academy of Sciences into the feasibility of harnessing the "new" work horse for naval propulsion. This committee, after almost two years of study, recommended the establishment of a naval gas-turbine program, including the construction and exhaustive laboratory testing of a gas turbine capable of sustained operation at 1500 F (3). With the adoption of this recommendation and the appointment of Dr. R. B. Kleinschmidt as the technical director of the program, the Navy embarked upon a long voyage during which we have seen lots of rough weather. However, in spite of metallurgical hurricanes, aerodynamic typhoons, and mechanical siroccos, subsequent events have established the wisdom of this basic undertaking.

To initiate the original program, a contract was negotiated in December, 1940, with the Allis-Chalmers Company for the design and construction of a 3500-hp unit suitable, not for installation in a ship, but for the laboratory investigation of those components which most logically might be used in a prototype shipboard plant (7).

This step was followed, a year later, by the setting up of a program of high-temperature-materials research at both the U. S. Naval Engineering Experiment Station (8) and the Massachusetts Institute of Technology (9).

Twelve months later, in 1942, two other laboratory models were placed on order. One of these, the Elliott 2500-hp unit utilizing Lysholm compressors, has been reported upon by several of the participating designers (10). The other, a 750-hp unit to be manufactured by the DeLaval Company (11), was to utilize a Birmann mixed-flow compressor, thereby providing a logical complement to the axial-flow and Lysholm machines already on order.

The year 1943 saw the Bureau of Ships extend its program to include two free-piston gas-generator projects (12), and a study of pressure-fired boilers, thereby completing the setup of a six-pronged assault on this propulsion gas-turbine problem.

These six projects have formed a framework or foundation structure for the work which has followed. An outgrowth of the original Elliott 2500-hp laboratory plant has been the authorization for the construction of a similar 3000-hp propulsion plant (13) intended for installation in a vessel. Literally hundreds of interlocking and dovetailing projects have been undertaken, ranging all the way from paper studies, accomplished by one engineer in a week, to the design, construction, and test of hardware involving a great many technicians for a great many months.

## OUTLINE OF PRESENT BUSHIPS ACTIVITIES

*Cycle Studies.* The wealth of literature available on the subject of the selection of the optimum cycle for a given application attests the magnitude of the task of arriving at any one answer, which, regardless of how intelligent it may appear at the time of design conception, will continue to appear intelligent throughout the three to five years which is normally required to bring that conception through the successive stages of detail design, component construction and testing, component alteration, and final plant assembly and testing.

Our work is further complicated by the several special requirements of a naval plant with which the designers of merchant marine, aeronautical, locomotive, or stationary gas turbines do not particularly have to worry. These special requirements are as follows:

*(a)* Excellent cruising, or light load, fuel economy plus good fuel economy at the higher loads as well.

*(b)* Maneuverability—that is, ability to accommodate rapid changes from low power (or dead-plant conditions) to high power to stop to back and again to high power ahead, etc., in any sequence and with great frequency.

*(c)* Air economy—the requirements for air must be reduced to the minimum in order that the size and the weight of intake and exhaust ducting do not become prohibitive.

*(d)* Resistance to severe shock or other battle damage.

*(e)* Economy of strategic materials—it would be foolishly shortsighted to develop, at great expense in time and money, prototype machinery which could not in wartime be reproduced in the required quantities because of the unavailability of metals or materials essential to its satisfactory performance.

All of these special requirements are combined in a naval plant with the several nonspecial requirements which are common to one or more of the other applications, such as the following:

*(a)* Reliability—certainly this requirement is common to all applications, but it is particularly important to aeronautical, merchant-marine, and naval plants.

*(b)* Minimum weight—this requirement is almost paramount for aircraft applications but it is only a little less important in naval installations because every pound that is spent on main engines means one pound less that is avail-

able for vital ammunition, guns, armor, or fuel oil. It is also important in lessening degrees to locomotive and merchant-marine plants.

*(c)* Minimum space—aeronautical, naval, and locomotive applications have this requirement in common although "frontal area" is probably the prime factor for aircraft engines whereas all dimensions are important to locomotives and naval craft.

*(d)* Accessibility or ease of maintenance—this requirement, which is seemingly incompatible with the weight and space limitations mentioned, is probably more important in naval installations than in any other because of the necessity of operating for weeks and months away from shore-based repair facilities. However, it is an important consideration in all prime-mover designs regardless of application.

To utilize fully the versatility of the gas turbine in meeting the maximum number of the foregoing general and special requirements, we have devoted much time and man power to the study of those variables which have a profound effect upon the character and performance of the resultant plant. Proper cycle selection is the framework upon which the elements of aerodynamics, metallurgy, and other engineering sciences are added to achieve the desired result. Studies have been made, and are constantly being revised, on all the various cycles, mechanical arrangements, and different types of components known to us. Here again, it must be pointed out that the scope of these studies has varied from a few engineer man-days to many hundred man-days, including in some cases laboratory substantiation of predicted results.

*Component Studies.* A re-examination of the initial program described at the beginning of this paper will recall to mind that many different types of components were included in the six original projects. Those original projects therefore afforded opportunity for the thorough exploration of the performance characteristics and construction techniques involved with axial-flow Lysholm, Birmann, free-piston, and controlled-piston compressors, and axial-flow reaction, axial-flow impulse-reaction, and Birmann mixed-flow turbines. The information generated by these investigations has been supplemented continuously by concurrent, or subsequent, studies of centrifugal, mixed-flow, and radial-inflow compressors, and of axial, radial-inflow, and radial-outflow types of turbines.

In addition to investigation of the many types of compressors and turbines indicated, the heading "Component Studies" must also include investigations such as that on extended-surface regenerators, various types of dynamic or "strong-wave" machines, the acoustic combustion chamber, various control devices, and control instrumentation.

*Material Studies.* The materials investigation programs at Annapolis and M.I.T. mentioned early in this paper have concentrated primarily upon the development and application of suitable high-temperature blade material and, as in all other phases of the over-all program, our efforts have been co-ordinated carefully with those of the dozens of other investigators working on the same problem. Those two projects have been concerned primarily with the conventional superalloys of the chrome-nickel-cobalt type, but very considerable additional amounts of Bureau time and contract money have been spent on ceramics, powder metallurgy, casting techniques (including grain-size control), welding techniques, and material-inspection methods.

*Turbine-Cooling Studies.* Periodic analysis of the work on cycle selection, component development, and materials research has led us to place increasingly great emphasis (in terms of percentage of available man power and money)

upon the development of suitable methods of cooling hot turbine parts in order to make higher top-cycle temperatures usable and/or to reduce the strategic material content required for satisfactory turbine life. The extremely encouraging results achieved in this respect at NACA as reported by Schey (14) and Ellerbrock (15), and the predictions of Hawthorne (16) have given us a good deal of faith in our own calculations. It would be hard to overstate the confidence which the authors have in the premise that some form of liquid cooling will be utilized on all naval and marine gas turbines in use ten years from the present. It appears that the future of air cooling for the hot turbine parts may not be spectacularly bright, but we believe that the field of liquid cooling offers a greater opportunity for clear-cut performance gains than any other one single line of exploration. Liquid cooling will probably be advantageous for all types of turbines regardless of application.

*Other Present Bureau Activities.* Security considerations prevent the further discussion of present Bureau activities along gas-turbine lines. It can be stated, however, as an index to this activity, that several top-flight gas-turbine manufacturers are presently engaged on construction contracts for the Bureau. These projects will be described publicly as soon as circumstances will permit.

## PROSPECTS FOR THE FUTURE

What this country needs is not more rosy predictions of a bright future for the gas turbine, but more down-to-earth certified performance records. This "Glamor Girl" this "Pin-Up of the Power Profession," as the gas turbine was so aptly described by Lester Goldsmith four years ago, has been all but murdered in her golden teens by exaggerated publicity, extravagant predictions, and overzealous enthusiasm. The rude shock incident to a realistic inventory-taking process has soured many individuals on the whole subject and has caused many capable open-minded engineers to develop a "show-me" type of sales resistance to any favorable statement made concerning the gas turbine.

This feeling is particularly difficult to combat in the field of locomotive, marine, and naval propulsion. It cannot be said, as it can of the aeronautical gas turbine, that a marine, locomotive, or naval gas turbine is a vital necessity. The existing machinery available for those three applications is far from being unsuitable, outmoded, or insufficient for the task assigned. In those fields, the gas turbine must show a positively advantageous balance against its competition in order to receive the high-level favor necessary for the release of the very considerable investment funds involved in the development of even a moderate size of gas-turbine installation. The task is made more difficult also by the fact that the short 500-hr life which is suitable for aeronautical uses has not heretofore been acceptable in the other applications regardless of how many other attractive features the arrangement may possess.

Nevertheless the authors of this paper still believe that a strong case can be made for the gas turbine in naval applications if sound judgment and foresight are compounded with skill, energy, and perseverance in the administration of each project.

A characteristic of a propulsion power plant for naval combatant service which is unique in the general marine picture is the very widely varying power requirement. If we consider, for example, a destroyer of recent years, statistical studies during both peace and wartime have shown that such a vessel operates for an overwhelming proportion of its

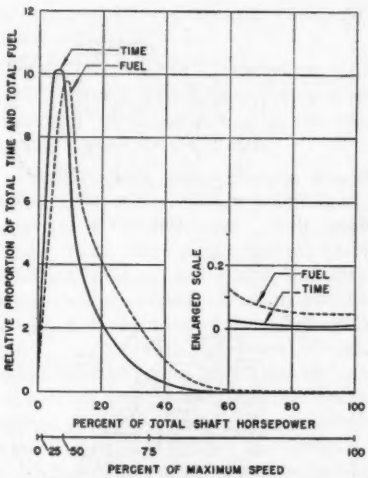


FIG. 1 RELATIVE STEAMING TIME AND FUEL CONSUMPTION OF AN AVERAGE DESTROYER AS A FUNCTION OF POWER REQUIREMENTS

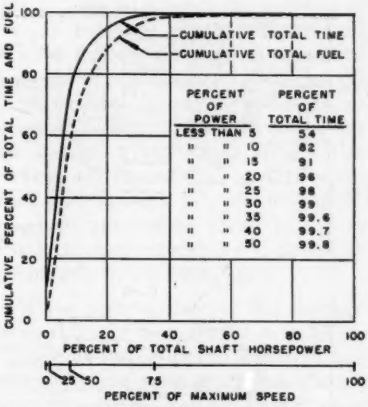


FIG. 2 CUMULATIVE PER CENT OF TOTAL STEAMING TIME AND TOTAL FUEL CONSUMPTION OF AN AVERAGE DESTROYER AS A FUNCTION OF POWER REQUIREMENTS

total operating life at a very low proportion of the installed power.

Fig. 1 shows the statistical average operating history of a large number of vessels over an extended period of wartime operation. Fig. 2, which is an integration of the curves in Fig. 1, indicates that the upper 80 percent of the installed horsepower is used for less than 4 percent of the operating life of the vessel; 70 percent for less than 1 percent; and 60 percent for less than 0.3 percent.

A representative figure for those machinery weights which are uniquely associated with the steam-propulsion plant of the vessels studied is 16 lb. per hp, including propulsion turbines, condensers and air ejectors, boilers, steam piping, blowers, feed-service pumps, tanks, heaters, heater-drain pumps, and circulating pumps. For a 60,000-hp twin-screw vessel (two identical 30,000-hp units), this means that for 99 percent of the operating life of the vessel (during which 97 percent of the total fuel is burned), 300 tons of propulsion machinery are carried about as a reserve against the sudden requirement for more than 30 percent power. The practicability of replacing this top 70 percent of installed power, which is required to operate for only 1 percent of the life of the vessel, with a relatively short-life gas-turbine plant weighing between ½ and 2 lb. per shp is attractive and appears feasible within the presently existing state of the art.

One of the several potential arrangements for accomplishing this desirable result is, we believe, especially worthy of description. This arrangement was first proposed, as far as we know, by S. A. Kane, then of the Bureau of Ships, in 1946.

*The Steam Cruising-Gas Booster Propulsion Plant.* Considering a 30,000-hp propulsion unit, this arrangement would involve 9000 shp of steam machinery and 21,000 shp of lightweight compact gas-turbine machinery. We would be able to design the steam plant especially for economical operation at the speeds for which it alone would be employed. Studies indicate that we should be able to utilize reduction gears of over-all size similar to those presently installed and to have both the steam-turbine

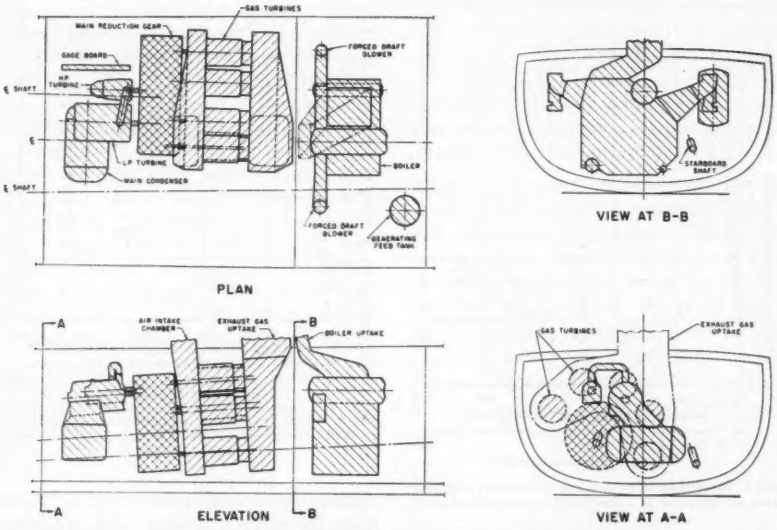


FIG. 3 DIAGRAMMATIC SKETCH OF PROPOSED STEAM TURBINE CRUISING-GAS TURBINE BOOSTER PROPULSION PLANT FOR ONE PROPELLER SHAFT OF A NAVAL VESSEL

and the gas-turbine torque delivered to this gear. If we conceive of the gas-turbine power being delivered by four to eight separate gas-turbine engines, we should then be able to separate these engines from the gear train by clutches when not in use.

The backing requirements, which for the ship under consideration would be of the order of 8000 shp (4000 hp per shaft) might be provided by astern wheels built into the steam-turbine castings in the conventional manner.

Fig. 3 shows a possible arrangement of this sort. Calculations indicate that such a plant may be built, within the framework of our existing knowledge, which would be competitive from a fuel-economy standpoint at all loads and still produce a net saving of about 260 tons (representing a 28 percent reduction) in ship's propulsion equipment, even if a conservative figure of 2 lb per hp is used for the gas-turbine elements. The length of the over-all machinery space would be reduced, relative to the former steam plant, by more than 10 ft.

The steam component included in this arrangement would consist of a cross compound turbine with a single-flow low-pressure element having the astern wheels in its exhaust casing. This turbine could be designed to give the maximum possible economy at the 20-knot point without undue sacrifice either at 9000 shp per shaft (which is the maximum power at which it would operate without gas turbines), or at 30,000 shp per shaft when operating in combination with the gas turbines.

Only one boiler per shaft would need to be provided since, in the event of a boiler derangement, the two steam plants could be cross-connected or the gas turbines operated alone if at least one of the five units per shaft were provided with a starting motor. Overheating of the steam turbine during operation with the gas turbines alone could

be avoided by maintaining a vacuum in the condenser.

The boilers, turbines, condensers, and auxiliaries are visualized as being conventional, nonexperimental in nature, having normal design factors.

The reduction gears likewise would follow conventional design practice, except as to arrangement. Each gear would have five single-helical first-reduction pinions and gears, and five double-helical second-reduction pinions spaced at 45 deg around the 130-in. bull gear. Two of the high-speed pinions would transmit power from a gas turbine as well as one element of the steam turbine. The other three pinions would transmit power only from gas turbines. A friction clutch of the Fawick-Airflex type could be incorporated in each first reduction gear in the gas-turbine power train.

The five gas-turbine elements on each shaft would be interchangeable. They would be adaptations of the now familiar 500-hr open-cycle, 2-shaft aircraft turbopropeller engine. Compressors would probably be axial flow and have a 10-to-1 pressure ratio. Combustion is accomplished in the familiar can-type chambers clustered about the central axis. The turbine-inlet temperature would be 1900 F, giving a design fuel rate of 0.6 lb per hp-hr at full power. The gas turbines should burn the same fuel oil as that used in the steam boiler.

The fuel economy of this combination steam and gas arrangement would be at least equal to that of comparable steam machinery at all speeds, and at the most important points, that is between 20 and 25 knots, it would be from 10 to 13 percent better.

The question may arise as to why, in a gas-turbine discussion, we have chosen for the base load or maneuvering plant a steam turbine rather than some configuration of gas turbines. Rather than that a lack of faith in the abilities of the gas turbine be inferred, it will here be noted that certain practical considerations have indicated the choice of the steam base-load plant. Sufficient emphasis must be given to fuel economy for the base-load or maneuvering plant (which will consume 97 percent of the total fuel burned) to require that the base-load gas-turbine plant, if one be installed, attain efficiencies at all speeds comparable to the steam plant.

At the present state of the development, this can be achieved only at the expense of increasing plant weight and volume by the addition of intercoolers and regenerators. The gas-turbine plant then weighs nearly as much as the steam plant. In addition, meeting the reversing requirements involves the use of either a controllable and reversible-pitch propeller or a reversing transmission between turbines and high-speed reduction-gear pinions. Either alternative will arouse a very vocal group of antagonists.

While we favor the development of the base-load gas-turbine plant as a definitely worth-while project which certainly will receive future attention, economy may dictate that its further development be postponed for the moment. There are, furthermore, certain advantages, primarily of a philosophical nature, which accrue from the retention of the steam plant: *(a)* It is thoroughly developed, proved and tested, and operating personnel are familiar with its use. *(b)* It permits retention of certain steam auxiliary machinery primarily in connection with the ship's "hotel" load. *(c)* Its life is long and its reliability, which is a prime requisite, is excellent. Although it may be a source of amazement to most of us, the question is asked occasionally, in all sincerity—"Will the gas turbine work?"—and to these skeptics, the presence of the steam machinery may be a reassurance.

## OTHER NAVAL APPLICATIONS

There are many other naval applications, of a special nature, to which the versatile gas turbine lends itself admirably by virtue of some one or more of its uniquely advantageous features. There are, for example, applications, such as motive power for emergency equipment with a very short operating life, and peak-load power for boats and vehicles, where the requirement of lightweight subordinates all others save reliability. Applications exist where fuels with the volatility of gasoline are not acceptable, and where at the same time powers are sufficiently high or weight limitations sufficiently low to preclude the Diesel. Other requirements exist for machinery of moderate weight but high power which are capable of almost instantaneous starting.

For all of the foregoing, some form of gas turbine will precisely fill the bill. For example, currently under development for the Bureau of Ships is a 400-hp gas turbine for emergency generator drive with a weight of 600 lb and designed life of 5000 hr (including 500 hr at full power). This prime mover supplants a Diesel engine weighing 8900 lb, thereby saving 8300 lb (93 percent of original weight) at no sacrifice, since fuel economy in this application is unimportant.

A gas-turbine prime mover for a portable fire pump shows promise of achieving a specific weight of 1.2 lb per hp for a 50-hp output, as compared with 3.7 lb per hp for its gasoline piston-engine predecessor. It has the added advantage of burning a nonvolatile nonexplosive fuel, which is for fire-fighting equipment definitely desirable.

## LONG-RANGE DEVELOPMENT PROGRAM

In looking into the less immediate future with an attempt to predict the direction in which further development should take place, consideration should be given to all of the naval-plant requirements described in the foregoing. It appears certain, therefore, that very great effort must be exerted toward the attainment of satisfactory performance of units operating at the very high temperatures above 2500 F. To us this means concentration upon the liquid-cooling principle with the personnel and money necessary to achieve the same high degree of development which has been attained by the automotive and aeronautical piston-engine fields. These efforts must be expedited because successful attack upon the problems will depend to a very great degree upon laboratory experimentation with working models, a process which is extremely time-consuming to say the least.

Likewise, in order to make most advantageous use of these high temperatures, after successful methods of handling them have been developed, the satisfactory and efficient production of much higher pressure ratios than those now in general use will be required. Therefore this calls for continued concentration upon the development of compact, lightweight, highly efficient compressors, and probably the more effective utilization of intercoolers or wet compression. As an interim future step, we recognize the potential merit of an all-gas-turbine propulsion plant of 30,000 hp comparable to the combined steam and gas plant described, wherein the cruising element is composed of a piston gas generator—gas-turbine arrangement and the booster or high-power plant is composed of straight-through units with 25:1 pressure ratio (achieved by suitable intercooling or water-injection methods), operating at an initial turbine temperature of 2500 F. or higher through the use of suitable liquid cooling of the hot turbine parts.

The problem of compressor fouling may well increase to such a degree as to make it desirable to give much greater emphasis to the development of the completely closed cycle than that which now exists. Reports being received from abroad on this subject indicate that our best efforts along the lines of development of the open-cycle units may be nullified by this matter of compressor fouling.

It seems wise, therefore, in planning a long-range program, to maintain a degree of flexibility which will permit the ultimate utilization of the closed cycle, both for realization of its own inherent advantages and for the contingency that the open-cycle-compressor fouling problem achieves dominating proportions. The closed cycle is so dependent upon the efficiency of its heat-transfer elements that the program for the future must include continued study directed toward the improvement of their performance and reduction of their size.

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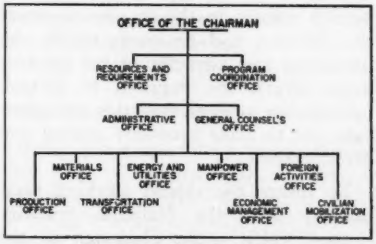
# THE NATIONAL SECURITY RESOURCES BOARD IN MOBILIZATION PLANNING

ACKNOWLEDGMENT

This article by Major JOHN D. MORGAN, Corps of Engineers, USA, discusses the basic organization and function of the NSRB in its relation to mobilization planning. The article is reprinted from the September-October issue of *The Military Engineer*. This paper, studied in conjunction with what actually develops as current mobilization is stepped up, provides an ideal to which an actual test can be applied much earlier than was expected.

World War II demonstrated to the United States the necessity of an integrated national effort in modern war. In order to provide the troops and the munitions essential for the Allied victory, controls of many types were required. In the confusion of the early days of World War II many of these controls were initiated and administered by different agencies that at times were working at divergent purposes when viewed from the perspective of the total national effort. As new problems arose new specialized agencies were established to deal with them, and then super co-ordinating agencies in the Executive Office of the President had to be organized. In many instances, the normal work of regular federal, state, and local agencies was overlooked, and competing or supplementary agencies were created. At the end of the war essential records in the hands of temporary agencies were frequently scattered and thus made inaccessible to regular agencies.

The need for decentralization of authority was apparent early in the war, but the regionalization schemes of many agencies had unrelated boundaries and headquarters in different cities, making more difficult co-ordinated solution of such problems as rationing, supplying electric power, drafting essential workers, expanding production, and civil defense.




Organization of the Staff of the NSRB

At the end of World War II the development of atomic bombs and other weapons of mass destruction showed that there would be no secure "Zone of the Interior" in a future war. It became apparent that the United States required a comprehensive program for its future security that would provide for the establishment of integrated policies and procedures for the departments, agencies, and functions of the government relating to the national security.

The National Security Resources Board (NSRB), a part of the Executive Office of the President, was established by the National Security Act of 1947. It is the function of the Board to advise the President concerning the co-

ordination of military, industrial, and civilian mobilization. The NSRB is concerned with the development of broad policies and programs designed to assure the effective mobilization and use in time of war of all of the nation's vital resources. Under consideration in this connection are such problems as the establishment of adequate reserves of strategic and critical materials and their conservation, the strategic relocation of key industrial and government activities, unified wartime efforts in all phases of logistics, and maximum utilization of manpower. The secretaries of seven departments—State, Treasury, Defense, Interior, Agriculture, Commerce, and Labor—are members of the Resources Board. In performing its functions the NSRB utilizes to the maximum extent the facilities and resources of the departments and agencies of the government, which are required to furnish information, reports, statistics, and other data and to make necessary studies and investigations.

To insure the closest working relationship with the National Security Council (NSC) the Chairman of the NSRB is a member of the NSC. Thus, resource considerations can be brought to the attention of the NSC when it carries out its duty to assess and appraise the objectives, commitments, and risks of the United States in relation to our actual and potential military power; to consider policies on matters of common interest to the departments and agencies of the government concerned with the national security; and to make recommendations to the President in connection therewith. The NSRB also works closely with the Bureau of the Budget and the Council of Economic Advisers.

In addition to the general functions outlined above, the NSRB has certain statutory responsibilities under which it advises the President concerning the placing of priority orders with industry for items required by the Armed Forces or the Atomic Energy Commission, and it co-operates with the Commissioner of Public Roads regarding the national defense aspects of highway planning.

The staff of the NSRB is organized into several functional groupings as shown in the accompanying chart. Coordinated planning has been initiated in two major fields: war mobilization planning, and peacetime readiness programs. Since the Munitions Board is the agency of the Department of Defense primarily responsible for planning the military aspects of industrial mobilization, it has been designated as the primary point of contact within the Department of Defense for staff members of the NSRB. Close ties on all staff levels exist between these two Boards. The NSRB looks to the Munitions Board for the collection of needed data from the operating elements of the Department of Defense and for refinement, analysis, and interpretation of such data. To prevent duplication, the NSRB and the Munitions Board use the same industry and interagency advisory committees wherever possible.

War mobilization planning requires identification and consideration of the many problems likely to arise in a future war. Of particular importance is the study of new problems which may arise in a future war for which there is no background of experience, although many of the unsolved problems of World War II, and even those that were satisfactorily handled in World War II also require attention. Two concurrent activities essential to all mobilization planning are the preparation of detailed estimates of both military and civilian requirements in a future war based either on consideration of future needs for specific end-items or on World War II experience, and the preparation of estimates of resources expected to be available in a future war. Resource estimates should set forth in detail the manpower, materials, facilities,

energy, and transportation expected to be available. A comparison of resources to requirements then reveals many deficits that will require either special mobilization plans or the alteration of strategic plans. Even if estimated resources appear to be adequate to meet wartime requirements, mobilization planning is required to insure efficient utilization of resources. Alternative solutions are sought which can be applied to circumstances as they may develop in a future emergency.

Peacetime readiness measures are programs that must be carried out in advance of an emergency to meet critical situations in which action can not be postponed until the actual outbreak of hostilities. Since the NSRB is a planning and advisory agency, it is primarily concerned with the policy governing current readiness measures. The strategic and critical materials stockpile program is an excellent example of a current readiness measure.[1] The Munitions Board serves as the central staff agency for the co-ordination of stockpile policies and programs, and it is advised by the Interdepartmental Stockpile Committee which brings together all the federal agencies concerned with stockpiling. The NSRB observer on this committee keeps the NSRB in constant touch with the status of the stockpile program. In 1948 the NSRB sent to the President a comprehensive recommendation covering steps necessary to accelerate the stockpile activity. This recommendation was approved by the President and then implemented by the several agencies concerned.

## WORK OF THE PLANNING OFFICES

While much of the work of the NSRB can not be discussed in detail for security reasons, a brief description of some of the work under way in the different planning offices shows the broad range of problems under consideration.

*The Resources and Requirements Office* has recently co-ordinated feasibility tests covering steel, copper, aluminum, petroleum, merchant shipbuilding, construction, and over two hundred selected key items of military equipment. These tests are intended to reveal to the NSRB and the Department of Defense whether strategic plans of the Joint Chiefs of Staff will be logistically feasible in war when considered in the light of national economic potentials and essential civilian requirements. Where deficits are indicated, special wartime mobilization plans are necessary; and, where no foreseeable means of overcoming deficits are apparent, strategic plans must be revised. Feasibility tests of the materials and items mentioned, and of many additional ones, are under continuous refinement, as the services develop better and quicker methods of determining accurate requirements based on strategic plans.

*The Program Co-ordination Office* insures proper balance among the different phases of mobilization planning, and develops planning assumptions that are consistent with the policies of the National Security Council.

*The Administrative Office* is concerned with providing all the facilities which are necessary in the execution of the NSRB's duties.

*The General Counsel's Office,* in addition to normal legal functions, such as commenting on legislation, has drafted an Emergency Powers Act which may be enacted by the Congress in the event of war or the threat of war. This Act is intended to provide the Executive

[1] See "Stockpiling for National Preparedness" by Maj. Gen. A. B. Quinton, Jr., in *The Military Engineer* for May-June 1950.

with powers that will insure the maximum utilization of the nation's productive capacity and its materials, and at the same time prevent excessive profits and speculation, maintain labor standards and the rights of workers to seek peaceful settlement of grievances without interrupting essential production, and maintaining a sound civilian economy and the equitable distribution of essential civilian goods.

*The Production Office* is developing broad programs to assure efficient production in such major areas as aircraft, construction and building materials, production equipment, motor vehicles and automotive equipment, transportation equipment, ships, scientific and technical equipment, construction and mining equipment, and engines and turbines. Joint NSRB-Munitions Board planning has dealt with the allocation of important segments of the nation's productive capacity. In an attempt to save time at the start of a war, special "phantom orders" for 100,000 critical machine tools were placed with manufacturers. These tools are expected to be produced immediately at the outbreak of hostilities without the delay that would normally ensue as military orders are placed with contractors and in turn with sub-contractors. Other phantom orders are being considered, as are overall priority, conservation, and limitation orders.

*The Materials Office* is developing mobilization plans for such basic materials as iron and steel, nonferrous metals, non-metallic minerals, light metals, chemicals, rubber, agricultural raw materials, and forest products. Much can be done regarding the basic materials even in the absence of firm wartime requirements for end-items, for it is obvious that most basic materials will be relatively scarce. The preparation of a series of materials surveys is presently under way. Several studies of world reserves of important mineral resources have been made and attention is being given to basic chemicals such as benzene, alcohol, and ammonia. This office also serves as the focal point for all NSRB activities in connection with the stockpile program, since most of the strategic and critical materials are raw materials.

*The Transportation Office* plans for the co-ordinated operation of domestic transport and storage, air transport, sea transport, and ports. In the field of domestic transport and storage a report and plan have been prepared by a committee headed by the wartime director of the Office of Defense Transportation. Task groups of specialists from industry and government are preparing additional reports covering railroads, streets and highways, inland waterways, pipelines, and storage facilities; are surveying ocean shipping problems including troop-ships, dry cargo vessels, tankers, and port utilization; and are also studying the mobilization of air transport.

*The Energy and Utilities Office* is responsible for mobilization planning for petroleum and petroleum products, natural and manufactured gas, solid fuels, electric power, and water and sewage works. Since many of the sources of energy are competitive there are many possibilities of combination, substitution, and integration that will result in greater efficiency in war. Planning is designed to curtail less essential uses while maintaining and expanding energy supplies for more essential consumers. National surveys of the supplies of and requirements for electric power and gas have been published and are being kept up to date.

*The Manpower Office* has prepared a preliminary list of occupations that would be critical in a war, and has specific plans for manpower surveys in some 200 industrial areas where large increases in labor requirements would be likely. Studies are under way covering occupational deferment policies, the procurement, distribution, and utilization of military personnel, labor-man-

agement relations, and wartime employment controls.

*The Economic Management Office* is planning an over-all wartime control structure into which can be integrated the many varied industry and commodity controls. Plans are being prepared for price controls, government procurement pricing, rent controls, rationing, and wage and salary stabilization.

*The Foreign Activities Office* has developed preliminary plans having the dual objective of increasing the economic strength of the United States and its allies and weakening the economic strength of enemy nations through interallied co-operation in such activities as import and export controls, preclusive buying, and mutual assistance in resources development and utilization.

*The Civilian Mobilization Office* is responsible for civil defense planning. It considers that civil defense is a national task which must be shared by all levels of government—Federal, State, and Local—with the Federal Government having the obligation of developing a National Civil Defense Plan and of furnishing to and through the states to the local governments needed information, advice, and guidance. A joint-staff study is now under way in Washington, D. C., Seattle, and Chicago to determine the probable effects of an atomic attack on a metropolitan area. Of particular interest to civilian and military engineers will be the series of information bulletins now being distributed by the NSRB: *National Security Factors in Industrial Location; Damage from Atomic Explosion and Design of Protective Structures;* and *Medical Aspects of Atomic Weapons.*

## CONCLUSION

The conversion of the normal peacetime economy of the United States to an arsenal of democracy in a future total war will be a tremendous task. If the outbreak of hostilities is unexpected and accompanied by significant destruction within the continental limits of the United States, the situation will be far more serious than at the start of World War II. Mobilization planning in advance of an emergency can be effective only if all phases are co-ordinated and carried on with the full co-operation of all concerned. Should this nation again be challenged, effective mobilization planning carried out prior to war should prove to be of great value in minimizing losses of lives, time, and resources, and in providing the strength needed to fight back.

# WHAT PRICE SPEED?

ACKNOWLEDGMENT

Messrs. G. GABRIELLI and TH. VON KÁRMÁN are the authors of this article on the specific power required for propulsion of vehicles. The article first appeared in *Mechanical Engineering* for October, 1950.

## INTRODUCTION

The history of technique and engineering testifies to the irresistible urge of humanity toward increasing the speed of locomotion. Means of locomotion on the ground, on the surface of, and within water, through the air, and perhaps through empty space, compete in an ever-growing effort toward higher velocities. Obviously, there are limitations for every type of locomotion. At a certain speed, any particular type becomes so inefficient and uneconomical that it is unable to compete with other more appropriate types.

It is difficult to find a measure of the comparative economy of locomotion, since it is impossible to find a general measure for the value of speed in human life. Obviously, speed has quite different value in war and peace, in transportation of persons, and of cargo. The appreciation of speed depends upon our whole philosophy of life, that is, on factors far beyond the scope of engineering science.

In this short study, the problem of comparative merits of various means of locomotion is considered merely from an engineering point of view. The power required for transportation of unit weight is used as a measure for the comparison. Evidently for a definite system of locomotion, the minimum of power necessary for transportation of unit weight is determined by the physical laws of the resistance of the medium, the efficiency of the method of propulsion, the unit weight and fuel consumption of the particular type of power plant, and many other factors. Nevertheless, it appears that if one throws all data together, a general trend, almost a kind of universal law, can be found for the power required per unit gross weight of the vehicle as a function of maximum speed. The demonstration of this general trend is the subject of the present contribution. One has to realize that the material is necessarily approximate and incomplete, and the conclusions are of rather tentative nature.

The data for power, weight, and maximum speed are taken, in general, from publications; the data concerning the products of the Fiat concern, from records of this firm. No classified material was used in the plotting of the diagrams.

The authors present their study in

this incomplete form to encourage a more complete compilation of statistical material by persons or organizations which are in a better position to do such work. They will be especially glad if manufacturers would speak up and show examples in which the power-weight ratio lies below the minimum curves shown in the accompanying diagrams.

A preliminary examination of the material has shown that it appears justified to separate the data for individual vehicles from the data for trains. It is known that, especially in the case of fast trains, the average resistance per vehicle is substantially smaller than that of a single vehicle. In the first part of this paper, we restrict ourselves to single vehicles. Table 1 gives the types of single vehicles to be considered.

TABLE 1. TYPES OF VEHICLES

| | | |
|---|---|---|
| I(*a*) Commercial ships | II(*a*) Motor-driven railway cars | III(*a*) Airships |
| (*b*) Battleships | (*b*) Trucks | (*b*) Helicopters |
| (*c*) Destroyers | (*c*) Automobiles | (*c*) Private airplanes |
| (*d*) Submarines on surface | | (*d*) Commercial airplanes |
| (*e*) Sumarines submerged | | (*e*) Bombers |
| | | (*f*) Fighters |

## METHOD OF PROCEDURE

The following procedure was employed in the evaluation of the material:

First, an extensive amount of material was collected for each type of vehicle and the power for unit weight (in hp per ton), calculated and plotted as function of the maximum velocity which the vehicle can reach in level motion. The values thus obtained show large dispersion. This appears natural since not all vehicles are designed with a view to obtaining the highest velocity with a minimum power per unit weight. Other factors, such as, for example, the price of manufacturing or design criteria incompatible with minimum power, may prevail. For our purpose, it seems to be logical to determine a limiting curve for each type representing the "minimum" value of the "power per unit weight" as a function of the "maximum velocity."

Hence, from the great number of vehicles of a given class, those examples were selected which have less power for unit weight installed than other vehicles of the same class and same maximum velocity. A continuous curve is plotted through the points representing these selected examples. It must be noted that this curve does not necessarily determine the minimum of the power that is required to transport one ton at a given velocity. It may occur that a vehicle built for higher velocity can be more economical at a lower speed, not using its full power, than a vehicle designed for the same lower speed as its maximum velocity. The exact meaning of the curve is the statement that, according to present experience, in order to design a vehicle of a certain type for a given maximum speed, at least as much power has to be installed as is shown by the diagram.

It must be noted also that the full power installed in the vehicle is used in the computations. This includes, of course, some power which is not used for production of thrust; for example, power used for auxiliary purposes. Also in the case of trucks and railway cars, a certain portion of the power is re-

served for climb. In other words, the maximum speed indicated in the diagram is, in general, less than the full speed which could be reached by the vehicle if the full power could be utilized on a horizontal track. These types of vehicles are often designed in such a way that the maximum power is not available for the horizontal run. To minimize this effect, such examples were selected for which the power reserve at the maximum speed is relatively small. On the other hand, the necessity of such power reserve corresponds to the nature of the vehicle and, therefore, it appears justified to use the full power for the comparison with other types.

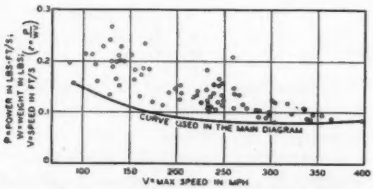



FIG. 1 EVALUATION OF DATA FOR COMMERCIAL PLANES

Fig. 1 represents an example of the evaluation of the data related to one type of locomotion, namely, commercial airplanes. The diagram contains 85 points representing 85 airliners—old and new—with a maximum speed between 80 and 395 mph. The nondimensional quantity $\varepsilon$ plotted as ordinate is the ratio between the maximum power $P$ and the product gross weight $W$ times velocity $V$. The quantity $P/V$ is the tractive force which would correspond to full use of the power $P$ for propulsion with a propulsive efficiency of 100 percent. Then $\varepsilon = \frac{P}{WV}$ is the ratio between this tractive force and the weight of the vehicle. Evidently, if one compares two vehicles and considers the work necessary for a given transport performance, i.e., the transportation of the same gross weight over the same distance, this work is directly proportional to $\varepsilon$. For example, in the case of commercial aircraft, the diagram shows that an optimum for power requirement exists at a speed of approximately 320 mph. As a matter of fact, the increase of maximum speed from 200 mph (say, from the DC-3) to 360 mph (Constellation or DC-6) has been achieved by actually decreasing the work necessary for the same transport performance. The amount of work increases only slightly if the speed is raised to 400 mph.

If we consider the propulsion problem from the viewpoint of the resistance of the medium, $\varepsilon$ is the ratio between a kind of total resistance which includes in addition to direct drag, the drag equivalent to losses in the transmission and in the propulsive mechanism—and the gross weight of the vehicle. It is a kind of global friction coefficient for the vehicle. We call it the coefficient of the specific tractive force or specific resistance.

It is apparent that this coefficient is useful for the comparison of different types of transportation, since it gives an indication of the price one has to pay in power for speed, and it helps to find out whether a certain system of transportation is suitable for further speed increase without penalty of higher specific-power requirement or whether one is near the economical limit. Of course the real measure of economy should be the work necessary to transport certain useful load, over a given distance. Therefore, our conclusions—in so far as economy is concerned—are strictly correct only if the ratio of useful load to gross weight remains constant. The authors hope that somebody will carry further the present analysis substituting the useful load for the gross weight. Since exact information concerning useful load is not easily available to the authors, they decided to use the gross weight as parameter.

In the following paragraphs we shall consider the three main classes of vehicles somewhat in detail.

## MARINE VEHICLES

Fig. 2 shows the curves representing the minimum specific power (i.e., built-in horsepower divided by gross weight), as a function of maximum speed for various types of single vehicles. Fig. 3 shows the specific tractive force, i.e., the power per unit weight divided by the maximum velocity. Both diagrams show that nautical vehicles have the lowest values for specific power or specific tractive force at least at low velocities. Evidently this fact makes ships the most economical single vehicles at low speed. The diagrams also show that for medium speeds the terrestrial and, for high speeds, the aerial vehicles represent the optimum cases.

Generally speaking, the power required for ship propulsion consists of four contributions:

*(a)* The skin friction acting on the wetted surface.

*(b)* The pressure drag produced by eddy or wake formation.

*(c)* The wave resistance.

*(d)* The air resistance of the superstructure.

The frictional resistance can be considered proportional to the square of the velocity, the density of the water, and the wetted-surface area, multiplied by a coefficient which essentially depends upon roughness of the surface, and a dimensionless parameter known as Reynolds number. For a smooth surface, the friction coefficient decreases with increasing Reynolds number, i.e., it is smaller for large boats than for small boats. For rough surface, the coefficient is essentially independent of speed. The eddy resistance behaves in general similarly to the frictional resistance. Fig. 3 shows that in the speed domain in which these two components of the resistance predominate, the specific tractive force, for example, in the case of merchant ships, shows a moderate increase with speed. For the same vehicle, the specific tractive force would be

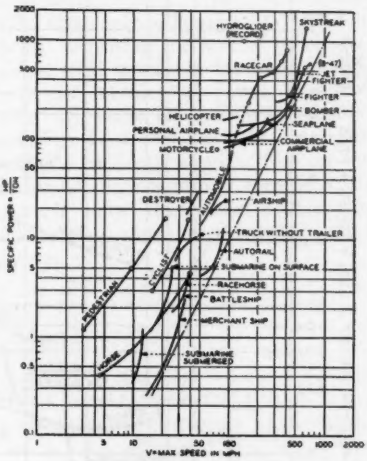



FIG. 2 SPECIFIC POWER OF SINGLE VEHICLES

approximately proportional to the square of the speed. However, if we consider ships of different sizes, then ships of large displacement are better off because the wetted surface increases more slowly than the displacement, i.e., the gross weight. Therefore, the increase of the specific tractive force in our diagram is much slower than that predicted by the quadratic law. It appears, nevertheless, that at least in the practical speed domain, the slowest ship requires the least tractive force.

On the other hand for both merchant and battleships, the specific tractive force shows a rapid increase in the speed range between 30 and 40 mph. The reason for this increase is the increasing wave resistance which depends upon another dimensionless parameter known as Froude number. This parameter may be defined by the formula $V/\sqrt{gL}$, where $V$ is the speed, $g$ the acceleration of gravity, and $L$ an appropriately chosen linear dimension of the ship, for example, the length of the water line. As the speed becomes of the same order

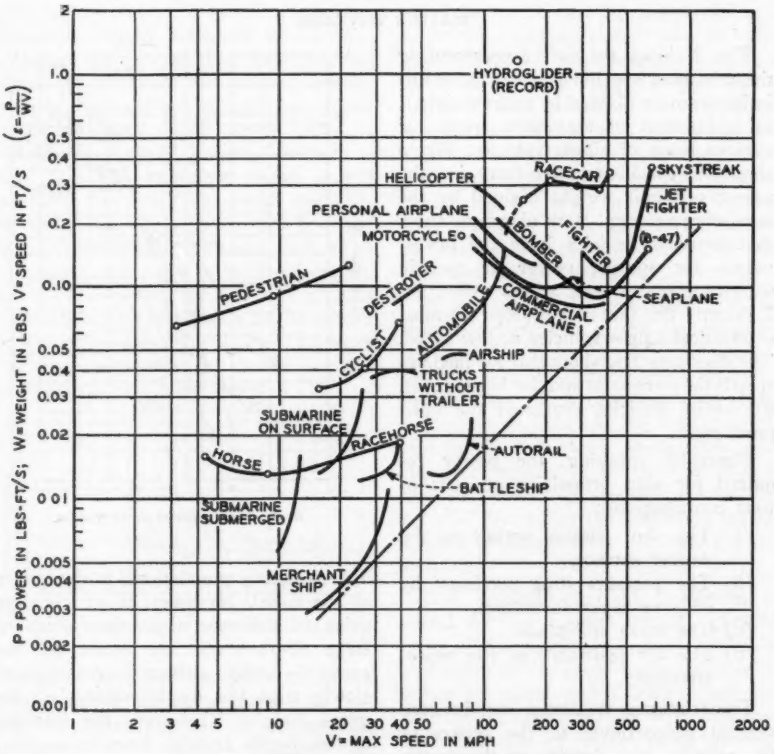



FIG. 3 SPECIFIC RESISTANCE OF SINGLE VEHICLES

of magnitude as the velocity of propagation of the predominant wave produced by the motion of the ship (which velocity is proportional to the quantity $\sqrt{gL}$), the wave resistance rapidly increases. The only effective remedy against this obstacle to speed increase is to increase the length of the ship. This measure is limited, however, by several factors, one of which is the increase of structural weight due to high bending moments, furthermore, capital investment, and also the practical limits of maneuverability. Docking and the like also limit the size of a ship. The compiled data show that, for example, in the case of merchant ships, the tangent to the curve shown in Fig. 2, at the present speed limit actually reached is about 6:1, which means that for a speed increase of about 1 percent, the built-in power per ton must be increased by about 6 percent. A similar result is shown for battleships. Evidently, these means of locomotion are approaching speeds at which further increases appear uneconomical.

The destroyers are shown in the diagram operating in the speed range between 35 and 50 mph. This operation requires about 8 times larger tractive force per unit weight as required, for

example, for a large commercial liner. Of course these vehicles are not built for economical operation at such high speeds. Their main feature is maneuverability in battle conditions. Their maximum speed is limited rather by cavitation characteristics of the propellers than by increasing wave resistance.

The specific tractive force required for the submarine on the surface is considerably larger than for merchant ships or battleships. This is due partly to the fact that they are not built primarily for surface locomotion and partly to the limitations of their size. The submarine in submerged state faces frictional and eddy drag only. The diagram shows a rather surprising increase of power required with increasing maximum speed. Such an increase of power does not seem necessary from a hydrodynamic point of view and must be connected with the particular specifications for the design of the submarines considered. It is to be noted that recent progress in submarine design is not included in our figures.

## TERRESTRIAL VEHICLES

The resistance of terrestrial vehicles can be separated into three components. These are as follows:

*(a)* Rolling friction.
*(b)* Air resistance of the body.
*(c)* Air resistance of the rotating wheels.

In addition, since our definition of tractive force is based on total power built into the vehicle, the transmission losses are included.

In examining Fig. 3, a large disproportion in specific tractive force required for trucks and passenger automobiles, as compared to rail cars, is evident. This is explained sufficiently by the difference in the rolling friction between pneumatic tires and road, as compared to the rolling friction between steel wheels and rail. In the case of the rail car, we find that at relatively low speeds (between 50 and 70 mph) the specific tractive force is essentially independent of speed. As a matter of fact, at these speeds the greatest portion of the total resistance is contributed by the roll friction which is essentially proportional to the load on the wheels and almost independent of speed. As the relative contribution of the air resistance increases, the specific tractive force increases. The rate of increase of $\varepsilon$, however, is not determined directly by the law of air resistance which would make the tractive force proportional to the square of the speed; the increase of power at a higher rate is due to several factors, such as the necessity of a climb reserve which prevents the use of the total power built in at high-speed level run.

Similar conditions prevail in the case of automobiles. A recent analysis carried out by Romani for the French Center for Studies in Automobile Engineering shows that in the case of a nicely streamlined automobile, which is supposed to have a drag coefficient equal to about 0.3, referred to the master cross section of the car, the air resistance becomes equal to the rolling resistance at a speed of about 40-45 mph. At higher speeds, the air resistance becomes more and more the controlling factor. For commercial passenger cars, 125 mph can be considered as the highest speed. The curve shows that also in this case the installed power per unit weight is larger than would be strictly necessary following the law of air resistance.

It is interesting to note, however, that the increase of power required is much more moderate for racing cars. This is due (1) to better streamlining, i.e., reduction of the coefficient of the air resistance; (2) to the fact that the design

of race cars allows the use of full motor power in level run at maximum speed. As a matter of fact, if we compare the specific tractive force for the car holding the present speed record with a standard passenger car which has 120-mph maximum speed, we find that the ratio between the respective values of the specific resistance is equal to about 3, whereas the ratio between the squares of the velocities is about 11. For vehicles of the same size and shape, whose resistance consists essentially of air resistance, the two ratios should be equal. Of course, in addition to the points mentioned in the foregoing, it must be considered that the rolling resistance is also reduced in the case of the racing car by use of special tires and roadbeds.

For motorcycles, only one point is shown in each diagram since there is little difference between the performance of different makes of motorcycles. The comparison shows that the motorcycle is a rather prodigal device for locomotion. This may be due partly to the relatively large air resistance which is produced by the wheel itself and the parasite drag of the bodies exposed to wind. It has to be pointed out, however, that the ratio of useful load to total weight is very favorable in the case of the motorcycle.

It is interesting to see that the tractive force of single trucks (without trailer) is practically independent of speed in the speed range between 30 and 50 mph where the rolling friction is the determining factor, and the curve representing trucks constitutes almost a continuation of the curve representing passenger automobiles.

## AERIAL VEHICLES

Aerial vehicles are predominant in the high-speed range, especially in the speed range above 150 mph. There is one notable exception, that is the lighter-than-air craft—the airship. In its own speed range, the airship appears several times more favorable—at least in the sense considered in this paper—than the helicopter. This does not mean, of course, that the airship can replace a helicopter. The latter is a short-range device, with excellent ability to take off and land almost everywhere. The airship is a long-range means of transportation requiring special landing installation. The specific tractive force of the airship is of the same order as that of the truck or the automobile. It is also seen that in the speed range in which airships were used, the specific tractive force does not show any increase with increasing speed. One may therefore conclude that it should be possible to design airships of considerably higher speed (say, 120 mph) without any significant increase of the work necessary for a given transport performance. For this aim, the size of the airships has to be enlarged considerably and this may require the solution of new structural problems as well as new methods of propulsion; significant aerodynamic improvements may also appear feasible. At present the difficulties of handling of very large ships and the need of relatively large capital investment seem to be the main impediments to the revival of airship development. On the other hand, its large cargo capacity and the comfort of travel yet may secure a place for the airship in transoceanic travel in a speed range between those of the large passenger ship and the commercial airliner.

Proceeding to some remarks concerning heavier-than-air craft—especially airplanes—let us consider Fig. 3, i.e., the diagram showing the specific tractive force as a function of the maximum speed. The large specific tractive force required at low speed is a characteristic feature of all airplanes. It is apparently an unavoidable consequence of the fact that the airplane has to provide its own sustentation by power. This is, of course,

also true in the case of the helicopter and of the bird-imitating ornithopter which, however, has not yet reached any stage of practical application. In so far as commercial air transport is concerned, this fact is a fundamental restriction in the application of the airplane. Whereas in the domains of ship, railway, and automobile transportation, it is possible to build high-powered fast vehicles for passenger transport and low-powered slow vehicles for inexpensive cargo, the same problem has not been solved yet so far as air transport is concerned.

Let us glance for a moment at the diagram showing the power required per ton for various airplanes (Fig. 2).

For all airplanes, the minimum number of horsepower required for 1 ton weight is greater than 110. This corresponds to a power loading of about 50 lb. per hp. This does not mean that no airplane can be designed to carry more than 50 lb. per hp. However, this value of the power loading appears at the present time as a highest limit for an economically possible airplane. It also represents a reasonable limit for take-off. To be sure, jet-assisted take-off may change the take-off limitations. One sees, furthermore, that the ratio between the speed of the fastest commercial airplane and the slowest private plane in use is about, 4.5:1, whereas the ratio between their specific powers is less than 2:1. There are two reasons for this fact: (1) Airplanes with low wing loading have, in general, relatively low structural efficiency. When the size of such a lightly loaded plane is increased, the empty weight goes up to such an extent that pay load and range shrink to small uneconomical items. (2) Small airplanes have in general a less favorable lift-drag ratio than large airplanes because the parasite drag constitutes a larger portion of the total drag. Whether a low-powered glider with excellent lift-drag ratio could reach sufficient popularity to make its manufacture and sale economically feasible, is yet an undecided question. Maybe if a small jet or turboprop engine could be manufactured at low cost, the present situation would change.

It has been mentioned already that the speed of commercial airliners has been greatly increased without penalty to their economy. In this development—in addition to aerodynamic improvements—the realization of high-altitude air transport played a significant role. The spectacular increase of speed of bombarding aircraft is due mainly to the increase of size and flight altitude.

It is quite instructive to look at the diagram representing the specific tractive force for airplanes (Fig. 3). By its definition, this quantity is equal to the drag-lift ratio of the plane divided by the propulsion efficiency. The optimum ratio for commercial airliners is about 0.08, corresponding to a lift-drag ratio of 12:1, or taking into account the propeller efficiency about 14:1. This figure is proof of the rather highly developed state of aerodynamic design. In the case of fighters, the optimum occurs at a speed of about 400 mph, and the best value is 0.118, which is yet an excellent figure if one takes into account the fact that fighters are not primarily designed for economy—that economy must be sacrificed for maneuverability and offensive armament, which means unavoidable parasite drag.

We have seen that in the case of ships, the increase of wave resistance at a certain Froude number increases greatly the power required. In a somewhat analogous way, the airplane has to overcome the so-called compressibility effects, when one approaches sonic velocity, i.e., Mach number 1. This is clearly shown in the diagrams. For example, in Fig. 2, the horsepower per weight ratio increases rapidly between 500 and 600 mph speed, and a corresponding increase of the tractive-force coefficient appears in Fig. 3. It is known, however, that by the use of so-called sweptback wings, the critical Mach number can be increased, and the rapid rise

of the drag delayed to a higher speed range.

The relatively favorable values for the B-47 bomber are probably due to the effect of sweepback. The data for fighters with sweptback wings are in general not yet available for publication, but they probably would yield points between those representing the Skystreak and the B-47 bomber.

There are no published data available for airplanes with supersonic velocity at level flight.

Our representation of jet planes is not quite consistent with that of propeller-driven airplanes. For jet planes, we used the static thrust of the engine divided by the gross weight of the airplane for the calculation of the specific tractive force. Similarly, we used thrust horsepower for the calculation of the horsepower per ton ratio. It was felt that it is difficult to say what is the meaning of "built-in power" in the case of the jet engine. The use of the thrust horsepower for the comparative computation gives some advantage to the jet engine, because in the case of the conventional airplanes, the shaft horsepower was used which is equal to the thrust horsepower divided by propulsion efficiency.

## LIVING VEHICLES

For curiosity's sake, the authors included some data concerning the man, walking and running, the man on bicycle, and the horse. They did not attempt to discuss quantitatively the case of fish and fowl, nor that of the man swimming in water.

The main difficulty in the case of a living power plant is the estimate of the effective horsepower, which greatly depends upon the duration of the effort used in locomotion. After consulting some publications on the matter, Table 2 was compiled and the data given in the table were used for the diagrams

TABLE 2 DATA ON LIVING POWER PLANTS

| Kind of locomotion | Weight, lb | Speed, mph | Power, hp |
|---|---|---|---|
| MAN—WALKING AND RUNNING | | | |
| Walking | 155 | 3 | 0.084 |
| Marching fast | 135 | 9 | 0.30 |
| 100-yard runner | 122 | 22.4 | 0.90 |
| MAN—ON BICYCLE | | | |
| Pleasure trip | 185 | 15.5 | 0.25 |
| Speeding on highway | 160 | 25.0 | 0.47 |
| On racetrack | 155 | 38.1 | 1.01 |
| HORSE | | | |
| With carriage, at fast step | 3500 | 4.5 | 0.64 |
| With carriage, trotting | 2650 | 9.0 | 0.85 |
| Racehorse in gallop, with jockey | 1000 | 38.5 | 2.0 |

It has to be realized that these data are somewhat arbitrary. Nevertheless, one can make interesting observations; for example, the power per weight ratio is almost identical for the fastest racehorse and the fastest battleship at about the same maximum speed. It is the belief of the authors that it would be of interest to analyze sport records concerning swimmers, marathon walkers, runners, horse and dog races, and the like, from point of view of the performance of the human and animal power plant.

## COMPOSITE VEHICLES

Composite vehicles are in use on the ground, on the water surface, and in the air. We want to restrict ourselves to the terrestrial vehicles. The tugboat is employed mostly for river and canal transportation, and at low speeds; it is rather impractical on high sea. The glider train has been used as an aerial composite vehicle, but the advantages of such an arrangement are not very great, in so far as saving of power is concerned. It has been suggested that aerodynamic advantages could be realized by coupling airplane wings end by end because the tip losses would be essentially reduced. Similar effect is realized in formation

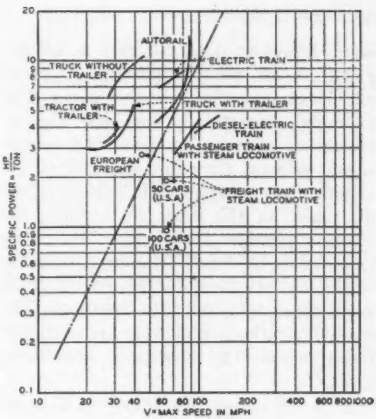



FIG. 4 SPECIFIC POWER OF CONVOYS

flight of birds and also of airplanes. There are, however, not many data available on this subject.

Fig. 4 represents the curves for power per ton at maximum speed for tractors and trucks with trailers and various types of trains. The reduction of power required per unit weight is due to several reasons: (1) Especially in the case of fast trains, the air resistance of the complete train is considerably less than the sum of the air resistances of the single cars used separately. (2) The concentration of the propulsive power in the locomotive allows the employment of large power-plant units, with better efficiency and lower specific weight. It is seen, however, that the trains driven by electromotors fed from power lines have higher power per weight ratio than, for example, the Diesel-electric and steam-driven passenger trains. They are even less favorable than single rail cars. The reason is probably the speed limitation by the method of transmission of electric energy from the power line to the locomotive. Because of this limitation, the designers of such trains may not have made such effort for power economy as, for example, have the designers of Diesel-electric trains.

The fast freight train is, no doubt, the most economical type of transport in the speed range between 40 and 60 mph in so far as power required is concerned. The data show a wide dispersion according to the different number of cars in the train and different size and design of the cars themselves. For American freight trains, one obtains a specific tractive-force coefficient of the order of 0.0025 at 60-mph speed, which means that a tractive force of about 5 lb is sufficient to move 1 ton weight at this considerable speed. This figure is to be compared with 0.04 for trucks at the same speed and with 0.08 for airplanes at a speed of 200-300 mph. Unfortunately, as it has been pointed out previously, it is not possible to construct airplanes with reasonable economy at low speeds in order to compete with the railroad in cargo transport. For a speed of 60-80 mph, the coefficient of tractive force would be of the order of 0.2. Consequently, the railroad men should have the consolation that the railway age is not yet terminated. The partial change over from railroad to trucks, which occurred in the recent past, is mainly due to the greater flexibility of the truck system and lesser handling costs of the cargo carried by trucks.

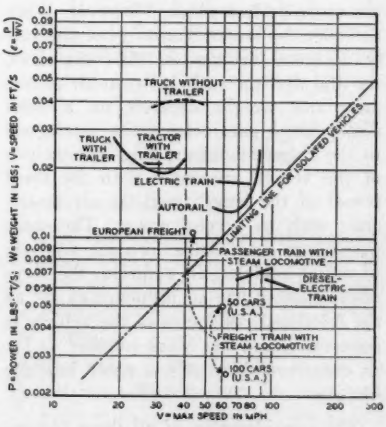



FIG. 5 SPECIFIC RESISTANCE OF CONVOYS

## GENERAL DISCUSSION

Let us return to the diagrams pertinent to single vehicles. We observe in both Figs. 2 and 3 that all curves lie above a certain limiting line. In other words, for every class of vehicle there is a certain limiting speed beyond which the vehicle becomes uneconomical. The increase of specific resistance with speed for a given vehicle is determined by the law of resistance for the method of locomotion considered. Such resistance laws, in general, depend on various characteristic dimensionless quantities. For example, the law of resistance for ships depends upon the Reynolds number and the Froude number. The Reynolds number determines the ratio between inertial and frictional forces. It contains the density and viscosity coefficient of the fluid medium, a characteristic length of the vehicle and its speed. The Froude number represents a ratio between inertial forces in the fluid and gravity. It is composed of the velocity of the vehicle, a characteristic length, and the acceleration of gravity. The law of resistance of terrestrial vehicles depends primarily on the coefficient of rolling friction and the coefficient of the air resistance. The best values of these coefficients for practically possible shapes are more or less given. However, if we consider the law of similarity of similarly designed vehicles of different sizes, we find that the ratio between air resistance and weight depends on a nondimensional parameter quite analogous to the Froude number, since the weight of the vehicle increases with the third power of the length, and the air resistance with its second power. The same parameter enters also into the analysis of aerial vehicles. In addition, the Reynolds number has an influence as far as the frictional resistance of the vehicle is concerned, and the Mach number as far as compressibility effects enter into the picture.

The consideration of all these parameters, however, does not give a full explanation of the limitations of speed which we investigate in this paper. For example, theoretically speaking, the increase of size or at least the length would prevent the rapid increase of resistance per weight ratio which limits the speed of the boats by keeping the Froude number sufficiently low. Why cannot this be done? Of course, increase of size has practical disadvantages which are difficult to be put into equations. The main limitations, however, are certainly those imposed by structural considerations.

It is necessary, therefore, to investigate which dimensionless parameters should be construed to express the similarity relations between structures of different sizes. The structural efficiency of a vehicle depends certainly on the specific weight $\gamma$ of the construction material and the allowable stress $\sigma_a$ for the same material. The ratio between allowable stress and the specific weight has the dimensions of a length so that the quantity $\gamma L/\sigma_a$, where $L$ represents the characteristic length of the structure, is a dimensionless quantity. As a matter of fact, if we replace the allowable stress by the ultimate stress $\sigma_u$ of the material, the quantity $\gamma L/\sigma_u$ becomes the ratio between the length of the vehicle and the so-called length of rupture of the material. The length of rupture is the length of a vertically hanging rod which would break under its own weight.

If we introduce such a structural parameter into our considerations, it appears more understandable that every class of means of transportation approaches a speed limit beyond which no practical design is possible. If we eliminate the length $L$ between the Froude number $V/\sqrt{gL}$ and the structural parameter $\gamma L/\sigma_u = \rho g/L\sigma_a$, we obtain a new parameter which can be written in the form $V/\sqrt{\sigma_u/\rho}$. It is easily seen that this parameter is dimensionless,

TABLE 3 COMPARISON OF $\sqrt{\sigma_u/\rho}$ AND $\sqrt{E/\rho}$ FOR VARIOUS MATERIALS

| Material | $E$, psi | Yield point, psi | Tensile strength, psi | Density $\rho$ slugs/cu ft | $\sqrt{\sigma_u/\rho}$ fps | $\sqrt{E/\rho}$ fps |
|---|---|---|---|---|---|---|
| Structural steel | $30 \times 10^6$ | 50000 | 80000 | 15.25 | 870 | 16800 |
| Stainless steel | $29 \times 10^6$ | 40000 | 80000 | 15.05 | 875 | 16600 |
| Heat-treated steel | $30 \times 10^6$ | 110000 | 150000 | 15.25 | 1190 | 16800 |
| Dural 24S-T | $10.4 \times 10^6$ | 48000 | 65000 | 5.4 | 1320 | 16650 |
| Titanium (at present) | $15 \times 10^6$ | 90000 | 120000 | 8.7 | 1410 | 15800 |
| Titanium (in development) | $15 \times 10^6$ | 150000 | 180000 | 8.7 | 1725 | 15800 |

since the quantity $\sigma_u/\rho$ has the dimension of the square of a velocity. As a matter of fact, the velocity $\sqrt{\sigma_u/\rho}$ can be given a mechanical interpretation. One can imagine a thin ring built of a material with the ultimate strength $\sigma_u$ and the density $\rho$. If one rotates such a ring with the circumferential velocity $V$, the quantity $\sqrt{\sigma_u/\rho}$ represents the speed at which such a ring would break under the action of the centrifugal forces.

It is interesting to compare approximate values of the quantity $\sqrt{\sigma_u/\rho}$ for various construction materials. Such a comparison is given in Table 3 for a few materials.

In addition to the stress-density ratio, the table also incorporates the ratio between elastic modulus and density. The quantity $\sqrt{E/\rho}$ has also the dimension of a velocity. As a matter of fact, it is directly proportional to the velocity of propagation of sound in the material concerned. It is remarkable that it has almost the same value for all the material considered in the table.

Since the stresses, in general, and especially dynamic stresses, are dependent upon the speed of the vehicle, and on the other hand a limiting line, which should be valid for all types of vehicles, cannot depend upon parameters containing quantities related to specific media or specific types of vehicles, it is probable that the values of the dimensionless parameters

$$V\Big/\sqrt{\frac{\sigma_u}{\rho}} \quad \text{and} \quad V\Big/\sqrt{\frac{E}{\rho}}$$

have a determining influence on the limitations of speed. The elastic modulus enters in the resistance against buckling and in the flexibility of the structure, which also may introduce limitations. In certain structures, for example, thin-walled so-called monocoque structures, combinations of the ultimate stress and the elastic modulus determine the allowable ultimate load. Hence both dimensionless structural parameters may have influence on speed limitations.

According to the evidence of our collected material, the minimum value of the specific resistance $\varepsilon$ of single vehicles seems to follow a trend which indicates that the over-all minimum value of $\varepsilon$ is approximately proportional to the speed of the vehicle. The equation of the limiting line shown in Fig. 3 would be $\varepsilon = .000175V$ where $V$ is the speed in mph. However, further analysis of the various vehicle systems is necessary to decide whether or not a general law expressed in the dimensionless parameters

$$V\Big/\sqrt{\frac{\sigma_u}{\rho}} \quad \text{and} \quad V\Big/\sqrt{\frac{E}{\rho}}$$

can be established.

It is, however, an interesting question whether, and in which way, further increases of velocity of locomotion may be possible without paying the penalty for speed.

First there is the question of how far propulsion efficiency can be increased. In most cases of vehicles of high-quality design, the propulsion efficiency is al-

most at the optimum limit. The improvement of thermodynamic efficiency of the power plants may radically change the range of various vehicles, but enters only indirectly into the consideration of the specific resistance or the power-weight ratio. For example, a prime-motor with lower weight and lower consumption may make it possible to increase the size of a boat in order to come into a more favorable Froude-number range without becoming utterly uneconomical.

There is also the question of novel methods of propulsion. For example, the drag coefficient of surface vessels may be decreased very essentially by lifting the bulk of the floating structure above the water level and supplying sustenation by hydrofoils. We do not attempt to estimate the effect of such a radical innovation. Whether the trials until now appear promising is a question of individual judgment. In the field of aerial vehicles, the longe-range rocket shot into high altitude and gliding from the ionosphere to a distant point on the earth may represent a new method of transportation. This case does not fit easily into our computations because it does not represent level flight but a combination of ballistics and glider technique.

According to computations of H. S. Tsien, a rocket with an average speed of 4500 mph over a 3000-mile range would require a thrust of 190,000 lb of 140 sec duration. This total impulse, distributed over the total flight duration of 40 min, corresponds to an average thrust equal to 11,100 lb. The initial weight is estimated to be equal to 96,000 lb and the final weight to 19,000 lb. With 57,500 lb as average weight, the specific resistance would be equal to $\varepsilon \sim 0.2$. This figure is, of course, excellent for such tremendous speed. On the other hand, the ratio between useful and total weight is extremely low as compared to level-flying aerial vehicles.

Disregarding, however, such speculative means of transportation, it appears from the considerations of this paper that probably substantial increase in speed could be realized if new materials with increased stress-density ratio could be made available. If the quantity $\sqrt{\sigma/\rho}$ could be increased essentially beyond the present limits, evidently the limiting line of the specific resistance versus speed would be displaced to higher values of the velocity. At a recent date, titanium alloys seem to give such promise. High-rate titanium alloys, manufactured at reasonable prices, may substantially change the results of the present analysis.

# FURTHER DEVELOPMENTS IN THE BURNING OF BOILER FUELS IN MARINE DIESEL ENGINES

ACKNOWLEDGMENT

Mr. JOHN LAMB'S article "The Burning of Boiler Fuels in Marine Diesel Engines" was reprinted by the Society in the JOURNAL for May, 1948. This article, describing further developments on that subject, is reprinted from The Transactions of the Institute of Marine Engineers for June, 1950, which Society published Mr. LAMB'S earlier article in 1948.

In December 1947 a full account of an endeavor to burn normal grades of boiler fuel in marine Diesel engines was given before this Institute.* The fuels used were of Venezuelan origin and had a viscosity range of from 1200 secs. to 1500 secs. Red. I at 100 deg. F. The ship used for these tests was the 12-knot 12,250 tons d.w. tanker *Auricula,* propelled by an 8-cylinder, 4-cycle type single-acting engine of Werkspoor design, rated at 4000 i.h.p. at 115 r.p.m. The *Auricula* was commissioned and began operating on high viscosity fuel in August 1946. Prior to these tests at sea prolonged experiments were carried out ashore.

Since that time a number of tankers of similar tonnage propelled by either Werkspoor, Burmeister and Wain, M.A.N., or Doxford engines have been equipped to burn such fuels. The results obtained in these ships have induced many owners to equip their motorships so that fuels ranging in viscosity from 40 secs. to 1500 secs. can be used, and the purpose of this paper is to pass on the results of further experience gained at sea in the burning of such fuels, and fuels of even higher viscosity.

To make an engine operate satisfactorily on 1500 secs. fuel does not mean that it will no longer burn 40/100 secs. Diesel fuel or any other fuel of intermediate viscosity. When equipped in the same manner as the *Auricula* the only effect of changing over from boiler fuel to Diesel fuel or *vice versa* is to alter slightly the revolutions of the engine. This, of course, is due to the lower specific gravity of Diesel fuel and a proportionately lower weight of fuel injected into the cylinders at each stroke of the pump for a given setting, so that the only adjustment required when making such a change-over is to advance the speed control lever until the revolutions of the engine are normal for the power that is required to be developed. For the best results it may be necessary to alter slightly the commencement of the fuel injection process.

* Lamb, J. 1948. Trans.I.Mar.E., Vol. 60, p. 1, "The Burning of Boiler Fuels in Marine Diesel Engines."

### COST TO EQUIP SHIPS TO OPERATE ON HIGH VISCOSITY FUEL

The work of equipping is now of a routine nature and is being carried out at various ship repair establishments in this country and on the Continent. The cost to equip a 4000 i.h.p. propelling installation whilst under construction is, as stated on previous occasions, in the region of £5000, but whereas in December 1947 the annual saving in the fuel bill of such an installation was a like amount, the difference between the purchase price of Diesel fuel and boiler fuel has widened so much that the annual saving of such an installation at the present time is nearer £8000, consequently the initial outlay is regained after seven-and-a-half months' operation on the cheaper fuel. The cost to equip existing ships varies according to machinery lay-out generally and particularly the arrangements originally provided for storing the fuel and heating it to pumpable temperatures, but in no case should the cost exceed £10,000.

### PERFORMANCE OF "AURICULA"

In August 1949 the *Auricula* completed three years' continuous sea service, during which the propelling engine operated for approximately 95 percent of the time on fuels ranging in viscosity from 1200 secs. to 1500 secs. Red. I at 100 deg. F. The reason why the engine did not operate wholly on such fuel was that for part of the first year Diesel fuel was used to maneuver in and out of port and during fog at sea until certain information regarding conditions produced when operating at considerably reduced power output could be obtained. During the second and third years the engine operated throughout on high viscosity fuels whenever such fuel was on board. On a few occasions high viscosity fuel was not available at the bunkering ports visited, and when Diesel fuel had to be shipped at ports abroad the surplus Diesel fuel was put ashore upon reaching a home port and 1200 to 1500 secs. fuel taken on board for the next outward voyage.

During the first three years' service the *Auricula* accomplished the following:—

| | |
|---|---|
| Distance covered between pilot vessels | 217,832 miles |
| Average speed at sea | 11.46 knots |
| Time operating at full power | 18,692 hours |
| Total number of revolutions made by main engine | 141,000,000 |
| Number of ports visited | 75 |
| Total quantity of high viscosity fuel consumed | 9009 tons |

The average cost of fuel during this three-year period was: high viscosity fuel 54.1s. per ton and Diesel fuel 90.7s. per ton.

During the three years the chief engineer was changed five times and the second engineer five times to comply with furlough regulations. The ship employs seven engineers and six greaser-firemen, the same as exactly similar ships the main engines of which operate on Diesel fuel. Whilst every endeavor is made to send ships away with at least one engineer on board who has had previous experience in the burning of high viscosity fuel, this has not always been possible, and in no instance has the engine suffered owing to absence of previous experience on the part of the engine-room staff.

The master of the *Auricula*, who has served in the ship since commissioning

except for periodical leave, was reported to have said in answer to an inquiry "The ship has given every satisfaction and been free from accidents. I have complete confidence in her. All her pilots have been very pleased and the experiment has turned out a complete success." The engineers who have had experience prefer to operate on high viscosity fuel because, they say, the exhaust valves do not require to be removed so frequently for overhaul and the engine runs more quietly than when operating on Diesel fuel. It has been proved again and again, by the master, that when in his cabin amidships, he can tell the moment a change in fuel is made, proving that what is commonly termed "Diesel knock" is eliminated. By "Diesel knock" is meant the sensation which is experienced in a motorship due to the rapid combustion of low viscosity distilled Diesel fuel. This Diesel knock, as is well known, can be felt but not heard, and there are a sufficient number of ships now in service to confirm that this elimination of the Diesel knock when running on high viscosity fuel is not peculiar to one particular engine.

At no time has the engine of the *Auricula* failed to respond instantly to telegraph orders from the bridge when operating on heavy fuel, even though on occasions the temperature of the engine-room at cylinder head level has been down to 40 deg. F. The involuntary stops at sea during the three years totaled 98 hours, 46 minutes, and of this total 54 hours and 23 minutes was the time taken to replace a faulty piston on one occasion and a cracked fuel valve body on another occasion. Neither of these failures had any connection whatever with the grade of fuel in use. The greater part of the remaining time that the engine was stopped at sea was during the first year's operation and was due to the high-pressure fuel pump plungers jamming, the necessity to tighten the camshaft driving chain, the renewing of a broken cylinder relief valve stud and changing supercharge air pump valves. Freeing fuel pump plungers accounted for 6 hours, 28 minutes and this time represents the total which can be attributed to the engine operating on high viscosity fuels.

The jamming of the plungers was due to the fuel pumps that were designed to handle Diesel fuel at atmospheric temperature being called upon to deal with viscous fuel heated to 180 deg. F. The trouble generally occurred when changing over from heated boiler fuel to unheated Diesel fuel and was caused by the sleeves contracting more rapidly than the plungers. Since the practice of maneuvering on Diesel fuel has been discontinued and the diametrical working clearance between plunger and sleeve was increased to 3/10,000 inch, no further trouble with the fuel pump plungers jamming when operating on either Diesel fuel or high viscosity fuel has been experienced.

In order that what is to follow will be more clearly understood, a sectional view through one of the cylinders of the *Auricula's* engine is shown in Fig. 1.

## CHIEF ENGINEER'S REPORT

Regarding what actually occurs in the engine-room of the *Auricula* the views of the men whose job it is to sail the ship will doubtless be of interest. A report received from the chief engineer after serving for one year will therefore be given, and the author's observations upon certain statements will follow. For reasons which will be appreciated the names of makers of certain parts referred to have been deleted. The report reads as follows:—

*"Fuel Combustion.* The burning of this type of fuel (1500 secs. viscosity) in the main motor proved very satisfactory. One very noticeable feature was

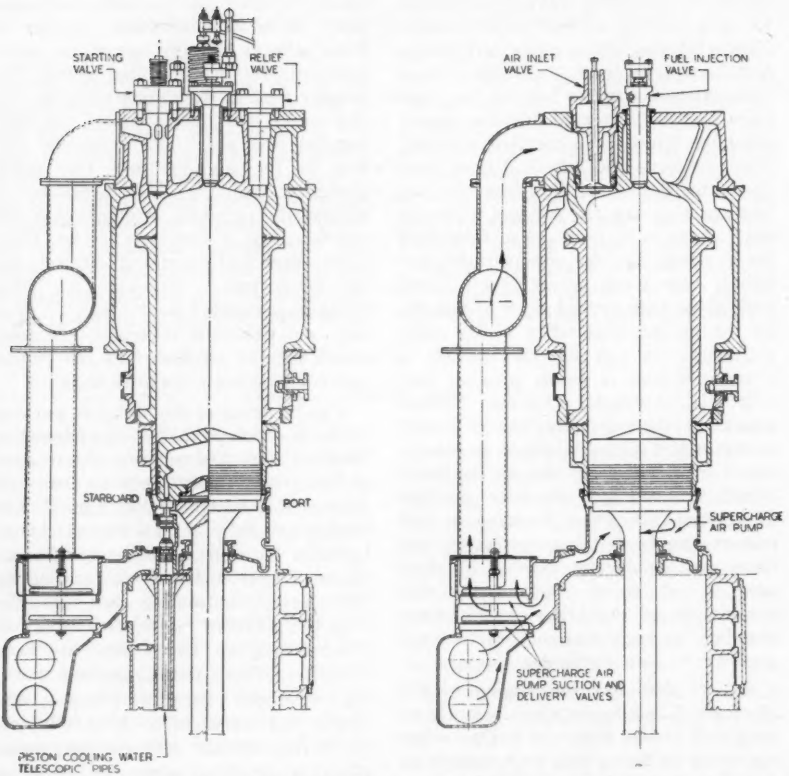



FIG. 1—*Section through a cylinder and under piston supercharge air pump of the* Auricula's *engine*

the fact that the life of the exhaust valve lids and seats was much longer when burning high viscosity fuels, than when the motor was burning marine Diesel oil. In fact, these valves were run for a period of 2800 hours (ship distance 31,275 miles) without showing any sign of pitting. The only fault to be found with their condition was the fact that the valve spindles were furred up to a depth of ⅛ inch below the spindle guide, also there was quite an accumulation of greasy carbon deposit in the pocket of the spindle guide. The main motor ran with an even turning moment, there being an absence of that slight firing knock observed when running on Diesel oil. It was found that the control of the desired temperatures for burning the fuel was very easily maintained. The fuel valves were generally run about 600 hours when they were removed for cleaning; this was mainly done to maintain the cooling water space in a clean condition; this fouling coming from the main motor piston cooling water system. The atomizers were always in good condition, all the holes being clear and no carbon found deposited on the tips of the nozzles. Carbon was at no time observed to have built up on the piston crowns but there was at times to be

seen a slight yellowish pattern of about 8-inch diameter on the piston directly under the fuel valve.

*Air Inlet Valves.* These valves were generally in a dirty condition when removed after 600 hours running; this being due to the unsatisfactory condition of the under-piston supercharge spaces.

*Fuel Valves.* Some trouble was at first found with the atomizers but this was traced to the type of atomizer manufactured by . . . The metal of which they were made was apparently not quite suitable. The needles were beating into the seats and so affecting the sharp admission and cut-off of the fuel. This type of atomizer was replaced by new . . . nozzles and they were found to be much more satisfactory. Trouble was experienced with the water jacket housings cracking at the top flange in way of the pressure housing holding down studs. The cause of this failure was probably due to the stress set up by the temperature of the independent hot water circulating system; this temperature was reduced from 160 deg. F. to 140 deg. F. Three such failures occurred in nine months; none fractured after the temperature was lowered.

*"Pressuretite" Joints on Fuel Pipe Connections.* These couplings were not entirely satisfactory. After having been in service for about 800 hours they generally start leaking. The serrations in the cone portion of the fitting work slack in time and wear away the pipe on which they are biting. A new ferrule cannot be fitted on the same place again. The pipe must be cropped before fitting a replacement, however, these fittings are not difficult to renew.

*Piston Cooling Water Telescopic Pipe Packing.* The life of the . . . rings on this motor was much shorter than was experienced on similar motors burning Diesel fuel. This may be due to acid acting on the canvas and deteriorating same and the oil acting on the rubber in the material. The fact that the water glands are not satisfactory allows water to be carried on the surface of the pipes and so into the under piston supercharge space. This is probably contributory to the forming of the emulsified deposit found in the supercharge spaces; also water entering this space may have an adverse action on the effective lubrication of the liner walls and piston rings. From liner and piston ring gaugings it has been observed that the greatest wear takes place in the athwartships direction, i.e., directly above the telescopic pipes and opposite them.

*Supercharge Air Spaces.* There is an accumulation of sludge formed here which builds itself up on top of the diaphragm plate and fouls the valves and trunks. It finds its way into the supercharge air manifold and air inlet pipes. It also finds its way past the piston rod scraper packing and so contaminates the crankcase lubricating oil. This sludge may be in part formed by the tarry substance, which adheres to the walls of the piston above the top ring, working its way past the rings and by the emulsification of the cylinder lubricating oil which accumulates on the diaphragm plate. It may well be that an answer to the problem of this sludge forming could be found by experimenting with a different grade of lubricating oil for cylinder lubrication.

*Crankcase Lubricating Oil Contamination.* The crankcase oil runs black and is found to accumulate a quantity of carbonaceous material which is removed by the purifier. The lubricating oil purifier is run 20 hours per day at sea. This carbonaceous substance resembles a black vaseline with little abrasive matter in it and finds its way into the crankcase from the upper side of the diaphragm plate past the piston rod packing. The condition of the bearings appears to be satisfactory but if this accumulation were allowed to increase it is possible

that trouble would be experienced with pipes choking.

*Fuel Purifying and Clarifying Plant.* No trouble was experienced with this installation at any time. The motors and purifiers were run about 13 hours per day at sea. The flat in which they were situated becomes very warm in tropical zones. The fitting of a forced system of ventilation here would improve conditions. It would be advantageous to have a light portable grating fitted around this plant about 4 inches from the deck to maintain a clean flat. There is no arrangement made for access to plugs at the bottom of purifier sumps.

*Main J.C.W. and P.C.W. Coolers.* Coolers scale up fairly rapidly. This is probably due to the higher temperatures carried in the fresh cooling water system and to the practice of circulating the coolers with warm sea water in preparation for starting the main motor. The coolers should be treated every docking or at regular intervals by the ship's staff to maintain them in an efficient condition.

*Heavy Fuel Heaters.* An alternative arrangement of heating the engine fuel should be made available in event of a failure of the heater. This could be arranged by connecting up one of the existing boiler fuel heating units.

*Summary.* The combustion of high viscosity fuel with the existing plant is a proved success. However, there are mechanical conditions which can be improved upon, such as the condition of the under piston supercharge spaces, which is contributory to the contamination of crankcase lubricating oil.

The main motor answered to all regulations of speed perfectly; indeed it was an event when a false start was registered while maneuvering and this was entirely due to the operator. It was easy to maintain a slow speed of 45 revolutions for quite a period of time. No trouble was ever experienced with the starting valves."

The author's observations on certain of the foregoing statements are as follows:—

The ⅛-inch thick deposit on the exhaust valve spindles referred to did not interfere in any way with the proper functioning of the exhaust valves. That the exhaust valve spindles had been copiously lubricated is evidenced by the statement "there was quite an accumulation of greasy carbon deposit in the pockets of the spindle guide."

The failure of the fuel valve housings mentioned by the chief engineer occurred only on the *Auricula*, where owing to a misunderstanding the circulating water in the fuel valve jackets was maintained at 160 deg. F. instead of 140 deg. F. when maneuvering on boiler fuel. In all other ships, where a temperature of 140 deg. F. was never exceeded, no such trouble was experienced, and, as mentioned in the chief engineer's report, no further trouble occurred on the *Auricula* after the temperature of the water in this particular part had been reduced to 140 deg. F.

The type of coupling used on the high-pressure fuel system, and referred to as giving trouble due to leakage after about 800 hours' service, is shown in Fig. 3. The leakage from such couplings is due to having to heat the high viscosity fuel before injection into the cylinders. At working temperatures the coupling expands to a greater degree

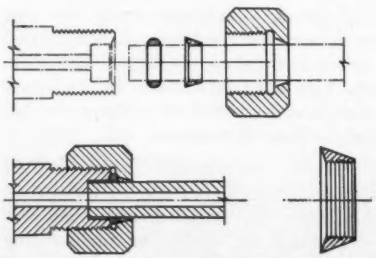


FIG. 3—*Section of a "Pressuretite" coupling used in the high pressure fuel system of the* Auricula

than with unheated Diesel fuel, and after a time the serrations become compressed and less effective. This would probably not occur if the couplings were tightened with only moderate force when cold.

There is no doubt that high sulphur content fuels have an injurious effect upon the types of packings usually employed in piston cooling water telescopic pipe glands. When the engine is burning Diesel fuel such packings require only to have a certain amount of resilience and be resistant to water and oil, but when burning high viscosity fuels the packings should, in addition to having the foregoing properties, be impervious to sulphuric acid. The arrangement of the telescopic pipe packing on the *Auricula* and other Werkspoor four-cycle engines is shown in Fig. 4. The purpose of the upper packing, which comprises three phosphor bronze rings, is to scrape from the pipes any matter which may blow past the piston and prevent it reaching the lower set of packing, the purpose of which is to prevent the escape of water from the piston cooling system.

When the engines were burning Diesel fuel both the oil and scraper packing and the water packing, shown at *(a)* Fig. 4, gave satisfactory results, but when the fuels used resulted in a corrosive acid being produced under slow running conditions and it became imperative that the packing should be completely effective, certain weak features of the packing were disclosed. For instance, referring to the oil scraper packing before alteration, the construction of the upper part of the housing is such that a well in which oil and solid matter from the bottom of the cylinder will accumulate is formed. The telescopic pipe is therefore constantly

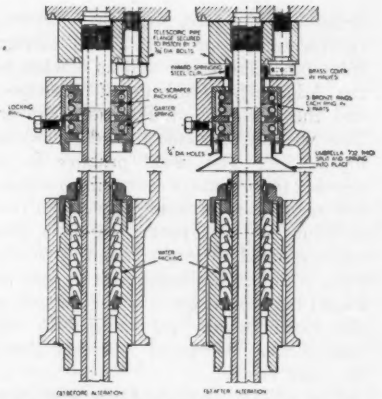



FIG. 4—Auricula's *piston cooling water telescopic pipe gland packing*

working through this oily matter and it is small wonder that some of it found its way past the packing rings. Another unsatisfactory feature is that any matter which should find its way between the scraper rings to the back of the packing is trapped. The means adopted to overcome these weaknesses are shown at *(b)* Fig. 4.

The accumulation of oily carbonaceous matter in the supercharge spaces under the main engine cylinders was most objectionable because some of it found its way into the crankcase and contaminated the lubricating oil. Moreover, the supercharge air spaces could only be cleaned manually, an operation which was looked upon with disfavor by the engine-room staff. The matter comprised a small amount of material from the lower ends of the cylinders, a moderate amount of lubricating oil which passed the piston rod oil scraper packing and a great deal of water from the piston cooling telescopic pipe glands.

## CONDITION OF PARTS AFTER THREE YEARS' SERVICE

After completing three years' service on high viscosity fuels the main engine parts of the *Auricula* likely to be adversely affected by operating on such fuels, such as cylinder head valves, cylinder liners, pistons, exhaust manifold and supercharge air spaces, were opened up and before any cleaning was

done, examined by over one hundred representatives of British and foreign shipping interests, as well as officials of the Admiralty, Ministry of Transport and the Ministry of Fuel and Power. This was the *Auricula's* third periodical drydocking. The usual practice is to drydock these tankers every nine months, but in order to preclude any suggestion of "nursing" the period for this ship was extended to twelve months. Moreover, whilst it is the practice to operate Diesel engines at about 5 percent below the rated power, the engine in the *Auricula* has developed 5 percent above the rated power.

The official record of the condition of the parts opened up, together with observations, is as follows:—

Of the eight air inlet valves Nos. 2 and 7 only were removed. The condition of the ground faces of these two valves was unchanged after 2228 and 1524 hours' service respectively, and after a layer of greasy matter had been removed from the upper surface of the valve lid and the inner surface of the valve seat the valves were re-fitted for further service.

The passages through which the air passed from the supercharge pumps, located under the working cylinders, to the air inlet valves were thickly coated with greasy matter which had obviously originated in the supercharge air pumps. In places the matter attained a thickness of 7/8 inch, which is too much even after three years' operation. The main objection to greasy matter accumulating in these passages is that a fire may be started in the event of an air inlet valve jamming in partly open position. The effect of a fire in supercharge air passages is to choke the engine and bring it to rest, after which the fire is quickly and automatically extinguished. In the

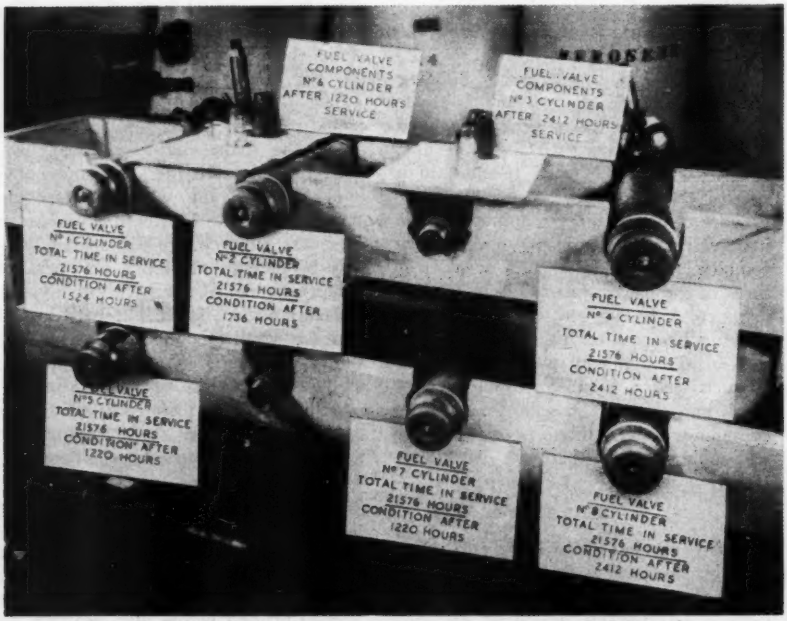

FUEL VALVE COMPONENTS Nº6 CYLINDER AFTER 1220 HOURS SERVICE
FUEL VALVE COMPONENTS Nº3 CYLINDER AFTER 2412 HOURS SERVICE
FUEL VALVE Nº1 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 1524 HOURS
FUEL VALVE Nº2 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 1736 HOURS
FUEL VALVE Nº4 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 2412 HOURS
FUEL VALVE Nº5 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 1220 HOURS
FUEL VALVE Nº7 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 1220 HOURS
FUEL VALVE Nº8 CYLINDER TOTAL TIME IN SERVICE 21576 HOURS CONDITION AFTER 2412 HOURS

FIG. 6—Fuel injection valves as removed from the *Auricula's* engine

case of the *Auricula* and other ships with similar engines, accumulation of greasy matter in the supercharge air passages was stopped when the formation of sludge in the supercharge pumps was eliminated in the manner already described.

An idea of the condition of the fuel injection valves when removed will be gathered from Fig. 6. All valves had been in use intermittently since the ship was commissioned and continuously prior to being removed on this occasion for the following periods:—

| *Valve* | *Hours* | *Valve* | *Hours* |
|---|---|---|---|
| No. 1 | 1524 | No. 5 | 1220 |
| No. 2 | 1736 | No. 6 | 1220 |
| No. 3 | 2412 | No. 7 | 1220 |
| No. 4 | 2412 | No. 8 | 1220 |

Just prior to entering drydock at Cardiff, where the inspection was carried out, the engine had operated continuously for two hours at 40 r.p.m. in order to avoid having to anchor until the drydock was ready to receive the ship.

All eight fuel valves were subsequently tested and all needles were found to be perfectly free and fluid-tight at 4000 lb. per sq. in. Not only was every hole spraying satisfactorily, but in no case was there any indication of carbon lining. The small quantity of deposit on the nozzles, which can be seen in Fig. 6, in no way interfered with the angle or direction of the fuel sprays.

Experience with sixteen ships propelled by Werkspoor, Burmeister and Wain, and M.A.N. four-cycle engines, burning high viscosity fuel in the manner described in the previous paper * has proved beyond all doubt that if the fuel valves and other factors which have an effect upon combustion efficiency are in good order, the fuel valve nozzles remain completely free from deposit so long as the engine is operating at more than three-quarters of its full rated power. The deposit which can be observed in Fig. 6, occurs only when the engine operates for long periods at greatly reduced speeds. Moreover, when the engine is again operated at full power the deposit burns off in a fraction of the time that it takes to build-up.

If close inspection is made of the three valves on the right of Fig. 6, it will be observed that a greater quantity of deposit is present on the nozzles of Nos. 7 and 8 valves than on No. 4. This may cause surprise when it is stated that No. 4 valve had been in continuous use for 2412 hours, or practically twice the number of hours to the credit of Nos. 7 and 8 valves. The explanation is, of course, that accumulation of deposit begins only when the speed of the engine is reduced, so that the quantity of deposit is no indication of the length of time the valves have been in continuous service. As more will be said later about the carbonization of fuel injection valve nozzles in general, and the fuel valves of the *Auricula* in particular, it will be observed from Fig. 6, that the deposit is well clear of the spray holes and that the bulk of the deposit occurs on one side only of the nozzle.

As in the case of the fuel injection valves, the exhaust valves of the *Auricula* had been intermittently in use for three years, and when inspected they had been continuously in service for the following periods:—

| *Valve* | *Hours* | *Valve* | *Hours* |
|---|---|---|---|
| No. 1 | 533 | No. 5 | 1524 |
| No. 2 | 533 | No. 6 | 1524 |
| No. 3 | 1524 | No. 7 | 1350 |
| No. 4 | 1524 | No. 8 | 533 |

In every case the internal surfaces of the valve housings and both sides of the lids were covered with a very thin layer of dry matter resembling ash, and in no instance had pitting of the ground mitre surfaces occurred. As a matter of routine the spare exhaust valves, with the exception of No. 1, were fitted after the

* Op. cit.

FIG. 7—Exhaust valve seat and lid after 2808 hours service on 1500 sec. fuel

inspection. No. 1 exhaust valve was re-fitted as taken out, and as the condition of this valve was typical of all others irrespective of time in service, the action taken is an indication of the condition of all valves. No. 1 exhaust valve, together with the fuel and air inlet valve, was re-fitted and will remain in service until defects are outwardly apparent in order to ascertain the greatest length of time such valves will remain serviceable when burning high viscosity fuel. This valve, as well as the fuel injection and air inlet valves, is still giving good service although the *Auricula's* engine has been operating exclusively on fuel having a viscosity of round about 3000 secs. Red. I at 100 deg. F. since August 1949.

Fig. 7 shows a dismantled exhaust valve head and seat as removed after operating for 2802 hours on 1500 secs. fuel. This length of time represents seven trips across the Atlantic, and 322,230 revolutions plus maneuvering in and out of seven ports. All who saw this dismantled valve at Cardiff will confirm that apart from a trace of deposit on the spindle and around the inside of the seat immediately above the mitre face, all parts, including the mitre faces of both the head and seat, were in a con-

dition which would justify the entire valve being refitted for further service.

On a great many occasions when more than usual trouble has been experienced with exhaust valves and piston rings leaking when burning Diesel fuel containing only a trace of sulphur, the sulphur has been held responsible, solely because sulphur can develop into corrosive sulphuric acid under certain conditions. Many, too, are convinced that if an attempt is made to operate a Diesel engine on fuels containing sulphur in any appreciable quantity, a new exhaust manifold would be required in a very short time.

There is no doubt that conditions productive to the formation of sulphuric acid in Diesel engines do occur on occasions, but experience with the *Auricula* and many other ships operating on fuels with a high sulphur content has proved that the corrosive effect on any engine part is negligible. It has been shown that when burning such fuels the sealing qualities of the piston rings are just as good as when burning sulphur free Diesel fuel, the exhaust valves actually remain in continuous service for a longer time and there was not the slightest sign of corrosion of the mild steel exhaust pipes on the *Auricula* after three years' service, during which time the engine consumed over 9000 tons of fuel having a sulphur content varying from 2.5 to 3.0 percent.

The clean condition of the exhaust manifold when opened up surprised many, one of whom was heard to remark, "I have a job at Falmouth that has been running for a shorter time on Diesel oil and you should see her exhaust pipe." The *Auricula's* exhaust manifold, which had received no attention for three years, was evenly covered with a film of soot of a thickness sufficient only to soil rather than black the hand when rubbed over the surface. The film on the portion of the surface immediately opposite the gas outlet from the cylinders was no different in composition or thickness from the film on any other part.

At the end of three years' service no measurable wear had taken place in any of the crankshaft, crankpin or crosshead bearings of the *Auricula,* and the steel bearing surfaces examined were of the usual brightness and quite free from any suggestion of corrosion. The inside of the crankcase, however, was rather dirty and the oil in a contaminated condition. This was not unexpected as the engine had operated nearly two years before effective steps were taken to prevent some of the sludge in the space under the cylinders passing into the crankcase with the piston rod. It will be recalled that the sludge comprised water leaking past the piston cooling telescopic packing, lubricating oil drawn out of the crankcase by the piston rod and carbonaceous matter from the bottoms of the cylinders. Prior to these matters being effectively dealt with the sludge accumulated on the top of the crankcases to a depth of from 1 inch to 3 inch in a year's operation, but now that leakage of oil and water has been stopped the average accumulation in a year does not exceed ½ inch, and in many instances the spaces are merely oily after an even longer period of service.

The rubbing surfaces of the cylinder liners were very smooth, being entirely free from scratches or pitting. In appearance there was no difference between the upper and lower ends, the entire surface of each liner being off-bright rather than highly polished. The cylinders had been lubricated at the rate of ⅞ gallon per cylinder per 24 hours and the slightly oily surfaces suggested that they had been adequately lubricated. The parts of the cylinders above the rubbing surfaces were entirely free from lubricating oil and fuel residues and in a condition generally which indicated a high degree of combustion efficiency.

Each of the eight 650 mm. diameter liners was gauged for wear at three

TABLE 1

| Cylinder | | Top | Middle | Bottom | Maximum wear, mm. | Mean wear | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Top, mm. | Middle, mm. | Bottom, mm. |
| 1 | F. & A. | 651·64 | 651·12 | 651·10 | 2·76 | 2·20 | 1·55 | 1·36 |
| | P. & S. | 2·76 | 1·98 | 1·63 | | | | |
| 2 | F. & A. | 1·02 | 0·80 | 1·00 | 1·71 | 1·36 | 1·07 | 1·09 |
| | P. & S. | 1·71 | 1·34 | 1·18 | | | | |
| 3 | F. & A. | 1·51 | 0·70 | 0·90 | 2·35 | 1·93 | 1·21 | 1·13 |
| | P. & S | 2·35 | 1·72 | 1·36 | | | | |
| 4 | F. & A. | 1·89 | 1·11 | 1·36 | 2·61 | 2·25 | 1·54 | 1·42 |
| | P. & S. | 2·61 | 1·98 | 1·48 | | | | |
| 5 | F. & A. | 1·54 | 1·37 | 1·46 | 2·41 | 1·97 | 1·54 | 1·53 |
| | P. & S. | 2·41 | 1·71 | 1·61 | | | | |
| 6 | F. & A. | 1·38 | 0·92 | 0·97 | 2·19 | 1·78 | 1·23 | 1·13 |
| | P. & S. | 2·19 | 1·55 | 1·29 | | | | |
| 7 | F. & A. | 1·67 | 0·70 | 0·68 | 1·67 | 1·62 | 0·82 | 0·93 |
| | P. & S. | 1·58 | 0·94 | 1·19 | | | | |
| 8 | F. & A. | 1·55 | 0·89 | 1·05 | 2·18 | 1·86 | 1·20 | 1·13 |
| | P. & S. | 2·18 | 1·51 | 1·21 | | | | |

points on their length and in a fore and aft and athwartships direction, the dimension obtained being as shown in Table 1.

It will be observed that, as is usual, the greatest wear occurs at the upper end of the cylinder in each case, the mean of all cylinders at the point of maximum wear being 1.87 mm. When these dimensions were obtained the ship had operated for 18,692 hours at full power and made a total of 141 million revolutions, so that the wear rates per thousand full power hours and per million revolutions are as follows:—

Per thousand hours..... 0.10 mm. (0.00394 inch)
Per million revolutions..... 0.0133 mm. (0.000524 inch)

From information disclosed recently in Sweden it would appear that some shipowners are finding that cylinder liners made after 1938 are less resistant to wear than liners made before that date. This has not been the experience with the fleet of over one hundred motorships of which the author has intimate knowledge. The average is still in the region of 4/1000 inch per thousand hours full power operation or 5/10,000 inch per million revolutions, the former excluding and the latter including harbor steaming. In some ships the average wear rate is, of course, higher, while in others the figure is as low as 0.050 mm. per thousand full power hours. Exceptional instances, such as the one referred to elsewhere in this paper which showed only 1.5 mm. wear after twenty-three years' service, are not included in these averages.

In examining the gaugings of the *Auricula's* cylinders, several interesting features are disclosed, but before discussing them the cylinder gaugings of an exactly similar engine, of about the same age, made by the same builders and operated continuously and throughout its life on Diesel fuel of between 40 and 100 secs. Red. I at 100 deg. F. will be given. At the moment the gaugings of four of the eight cylinders only of the M.S. *Elax* are available but those

TABLE 2

| Cylinder | | Top | Middle | Bottom | Maximum wear, mm. | Mean wear | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Top, mm. | Middle, mm. | Bottom, mm. |
| No. 1 | F. & A. | 651·78 | 651·20 | 651·00 | 2·33 | 2·05 | 1·46 | 1·05 |
| | P. & S. | 2·33 | 1·73 | 1·11 | | | | |
| No. 3 | F. & A. | 1·41 | 1·00 | 0·82 | 2·07 | 1·59 | 1·53 | 1·05 |
| | P. & S. | 1·78 | 2·07 | 1·29 | | | | |
| No. 6 | F. & A. | 0·75 | 0·53 | 0·33 | 1·15 | 0·95 | 0·73 | 0·44 |
| | P. & S. | 1·15 | 0·93 | 0·55 | | | | |
| No. 8 | F. & A. | 1·00 | 0·75 | 0·93 | 1·25 | 1·12 | 0·85 | 0·77 |
| | P. & S. | 1·25 | 0·95 | 0·62 | | | | |

shown here were obtained after 17,126 full power hours as against the *Auricula's* 18,692 hours, which is sufficiently close to make the comparison with the cylinder wear on the *Auricula* of value. The total revolutions made in each case were: *Auricula* 141 millions and *Elax* 108.9 millions. All cylinders of the *Elax* will have been gauged in the near future when the complete gaugings will be given. In regard to the manner in which these two ships have been operated, it might be mentioned that the *Elax* has traded in eastern waters most of the time while the *Auricula* has operated throughout on the Atlantic. Moreover, the engines of the *Elax* have been run in a normal manner, while during the first year of the *Auricula's* service the engine was operated under conditions which could be expected to result in excessive cylinder liner wear. For instance, the engine was run for long periods on greatly reduced supercharge air pressures and fuel injection pressures and temperatures considerably below what has proved to be necessary for proper combustion. Furthermore, the *Auricula's* engines have developed approximately 10 percent more power than the engines of the *Elax*.

Particulars regarding the wear which has taken place in Nos. 1, 3, 6 and 8 cylinders of the *Elax* are given in Table 2.

In comparing the cylinder liner wear rates of the *Auricula*, which has operated on high viscosity boiler fuel, with those of the *Elax*, which has run solely on Diesel fuel, it will be seen that there is very little difference. As the two ships have been running into ports where the amount of harbor steaming is widely different the most accurate basis for comparison is on the total revolutions made by each engine. If the mean of the wear at the upper end of the eight cylinders of the *Auricula* be compared with that of the four cylinders of the *Elax* on this basis it will be seen that the wear rates per million revolutions are:—

*Auricula* ..... 0.0133 mm. $\left(\frac{5.2}{10{,}000} \text{ inch}\right)$

*Elax* ..... 0.0131 mm. $\left(\frac{5.17}{10{,}000} \text{ inch}\right)$

Some might take exception to eight cylinders of the *Auricula* being compared with four cylinders of the *Elax* but, as mentioned earlier, the eight cylinders of both ships will be compared when accurate gaugings of the remaining cylinders can be obtained from the *Elax*. The information so far to hand

indicated that, as regards wear, No. 6 is by far the best cylinder on the *Elax*, and that when the final figures are received the average wear rate per million revolutions will be greater than that of the *Auricula*.

In the earlier paper* it was stated that there appeared to be a considerable difference in the wear-resisting properties of piston rings offered by different makers, and that it was the intention to make a closer study of this matter. Consequently the pistons of the *Auricula* were removed more frequently during the second and third years than would otherwise have been the case, in order to gauge the rings and cylinder liners for wear. When, therefore, the pistons were exposed at Cardiff in August 1949 the piston rings had been in continuous service for the following periods:—

| *Piston* | *Hours* | *Piston* | *Hours* |
|---|---|---|---|
| No. 1.... | 1,704 | No. 5.... | 12,140 |
| No. 2.... | 10,612 | No. 6.... | 6,900 |
| No. 3.... | 1,704 | No. 7.... | 10,612 |
| No. 4.... | 1,704 | No. 8.... | 10,612 |

Without a single exception every piston ring was not only free in its groove but was rotatable with the fingers, while in every case the piston crown was entirely free from carbonized lubricating oil or fuel. A small quantity of carbonized lubricating oil was present on the sides of all pistons above the top piston ring groove, and a smaller quantity between the grooves. The condition of No. 1 and 5 pistons as taken out can be seen from Figs. 8 and 9. These two pistons are typical of the condition of the remaining six pistons when removed and before any cleaning was done.

The remarkably clean condition of No. 1 piston (Fig. 8) after 1704 hours, excluding harbor steaming, will be noted. No. 5 piston shown in Fig. 9, is not quite so clean, but when it is remembered that this piston was in continuous service for 12,140 hours, excluding harbor steaming, which represents

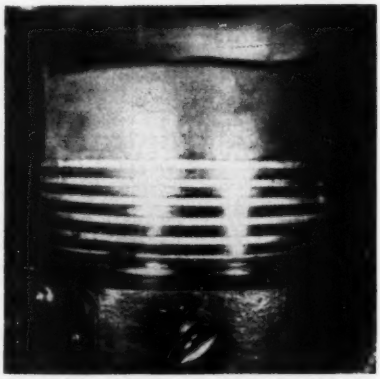


FIG. 8—No. 1 piston as taken out after 1704 hours continuous service

two years in the life of a tanker and 2.5 years in the case of a general cargo ship, it will be agreed that if the engines had been operating for this length of time on Diesel fuel such a quantity of deposit would not have caused any surprise. The photographs of these two pistons were selected for reproduction solely because they represent the shortest and longest periods of continuous service, and so will enable some idea to be formed of the rate at which the

FIG. 9—No. 5 piston as taken out after 12,140 hours continuous service

* Op. cit.

carbonaceous matter accumulates when burning boiler fuel.

Even the small quantity of carbonaceous matter formed over such a long period is not wholly attributable to the burning of boiler fuel, as the following analysis of a sample of the deposit will testify:—

| | |
|---|---|
| Microscopic appearance ..... | Black, soft dry flakes. Irregular black solid particles with few small globules of liquid. |
| Carbonaceous matter ..... | 70 percent weight. |
| Oil ..... | 19 percent. |
| Water ..... | 5 percent. |
| Ash ..... | 6 percent. |

A breakdown of the ash disclosed its composition to be as follows:—

| | |
|---|---|
| Water soluble ash..... | 22.4 percent. Mainly sodium sulphate with high proportion of vanadate. |
| Acid soluble ash..... | 72.9 percent. Mainly iron compounds with trace of calcium. |
| Acid insoluble ash..... | 4.7 percent. Mainly silica. |

While a proportion of the deposit emanates from the lubricating oil, and as the soluble ash not extracted from the fuel by the purifying plant does not result in greater cylinder liner wear than when burning Diesel fuel, it is reasonable to suppose that even better results as regards cylinder liner and piston ring wear would be obtained if the whole of the ash could be extracted before the fuel enters the cylinders. This matter is being given particular attention at the present time and if anticipated results are obtained the wear rate of these vital parts will be reduced very considerably below that which is now looked upon as normal, irrespective of the grade of fuel used. The aim, in other words, is to eliminate, so far as the fuel is concerned, the only cause of cylinder liner wear when burning high viscosity fuel and obtain the fullest advantage of the slower burning rate of such fuels, which is conducive to the maintenance of the lubricating oil film and, consequently, reduced wear.

During the *Auricula's* first year's service the piston rings in each of the eight pistons were supplied by the same maker and, presumably, were of the same composition and physical properties. At the end of the year the amount of wear that had taken place in a radial direction was found to be excessive, and during the second and third years, piston rings from various sources were tried out.

It is the author's experience, and doubtless the experience of many others, that piston ring wear varies considerably, not only between ships having exactly similar engines, but in the cylinders of the same engine. This suggests that the rate of wear does not depend solely upon the composition or physical properties of the rings and the liners against which the rings bear. The effectiveness of the lubricating oil film in preventing metallic contact is of prime importance and the thickness of an oil film can be reduced by unequal power distribution, late injection of fuel, improper spraying of the fuel, insufficient injection of lubricating oil or leakage of water into the cylinder or on to the liner, any of which faults can

occur in one or more cylinders of a multiple cylinder engine. If, therefore, a true comparison in the wear rate of piston rings from various sources is to be made, particular care must be taken to obviate any of the faults just mentioned occurring, and when such faults do develop the rings in the cylinder affected must be eliminated from the test and only those rings compared which are known to have operated under apparently normal conditions.

After the first year's service the rings in each of the eight pistons of the *Auricula* were replaced by new rings from the same source as the original rings, because it was concluded that although the original rings had worn excessively the conditions under which they had operated were abnormal. It will be recalled that during the first year at sea the *Auricula's* engines were purposely operated under exacting conditions in order to obtain information regarding the behavior of the engine when operating under all unusal conditions that could possibly be encountered in service. After a few voyages across the Atlantic, during which the piston rings operated under normal sea conditions, the capabilities of the rings, as regards resistance to wear, that were fitted at the end of the first year's service had been determined and recorded, and rings obtained from other sources were fitted. When the ship arrived at Cardiff in August 1949 after three years' service and two years after the careful investigation into the wear-resisting properties of piston rings had begun, the pistons contained rings from four different sources. All these rings were removed and the radial thickness measured at nine equally spaced points to ascertain the extent of wear, and the mean wear of each set of rings is shown in Table 3 together with the number of hours in continuous service and the wear rate per thousand hours of each set. It is to be regretted that the composition of the rings cannot be given but in the majority of cases what is considered by many to be the most important physical property, namely, the Brinell hardness figure, is given. The radial thickness of the rings when new was 21 mm. and the depth 13.8 mm.

TABLE 3

| Piston No. | Make of rings | Brinell No. | Hours in service | Radial mean wear, mm. | Mean wear 1,000 hrs., mm. |
|---|---|---|---|---|---|
| 1 | V1 | 168 | 1,704 | 0·376 | 0·221 |
| 2 | W1 | 180–210 | 10,612 | 4·150 | 0·391 |
| 3 | X1 | 196 | 1,704 | 0·247 | 0·145 |
| 4 | V2 | 168 | 1,704 | 0·603 | 0·354 |
| 5 | V3 | 168 | 12,140 | 4·440 | 0·362 |
| 6 | X2 | — | 6,900 | 2·170 | 0·310 |
| 7 | V4 | 168 | 10,612 | 2·510 | 0·236 |
| 8 | Y1 | 210–275 | 10,612 | 3·540 | 0·312 |
| ex 1 | Z1 | 190–220 | 6,929 | 6·680 | 0·964 |
| ex 3 | V5 | 230 | 12,015 | 3·100 | 0·258 |

Considering that all these piston rings served in cylinder liners of the same composition and operated under normal conditions, the great difference in their wear-resisting properties is, to say the least, enlightening. In addition a study of the results shown disclose the following:—

(1) Although the rings W1 and Z1 have approximately the same Brinell hardness figure the wear rate of the Z1 rings is two-and-a-half times that of the W1 rings.

(2) That the rings V1 and V2 were from the same source and presumably of the same composition and physical properties and had been in service for the same length of time, yet the wear rate of the latter is 50 percent greater than that of the former set of rings.

(3) The rings W1 and V4 had been in service for the same length of time and the wear rate of the harder rings was 1.2 times that of the softer rings.

(4) Although the rings V4 had been in service for a very much longer period than the rings V1 and V2, all of which were from the same source, the wear per 1000 hours was almost as good as the wear rate of V1 rings and better than that of V2 rings.

From the results of these tests one is forced to the conclusion that users of piston rings have as yet no yardstick by which to judge the wear-resisting properties of such vital parts, and that some manufacturers might make a closer study of the conditions to which their products are subjected in order that shipowners may get better value for money. At the moment it would appear that the motor and aeronautical industries are much better served in this respect.

It is usual and natural when studying piston ring wear to consider the effect on cylinder liners, since the general opinion is that either one or the other must wear and it is better that the piston rings rather than the cylinder liner should wear. For the benefit of those holding such views it should be mentioned that in the case of the *Auricula* any deduction made on this basis would be inaccurate, because piston rings from various sources had operated in all cylinders.

The wide-spread belief that piston rings should be made of cast-iron somewhat softer than that of the cylinder liners so that the rings rather than the liners shall wear, cannot, it is suggested, be substantiated either by experience or logical reasoning. If piston ring material is purposely made so that the rings will readily wear, the manufacturers of the rings will certainly benefit, but there is no such certainty that the cylinder liners will also benefit. Surely, if fine particles of cast-iron are mixed with oil a very effective grinding paste is formed. The author recalls that during the early days of the marine Diesel engine when numerous small case-hardened engine parts such as fuel pump plungers, fuel valve spindles, etc., became worn and required attention on board, the most effective way of truing-up was to revolve the part at high speed in the lathe and lightly press the end of a soft copper rod against the part while feeding-in fine carborundum powder and oil. Copper was selected for the purpose because of its softness, since the softer the material the more readily did the carborundum become embedded and the more effective was the grinding tool.

## CYLINDER LINER AND PISTON RING MATERIAL

Gray cast-iron has long been the standard material for cylinder liners and piston rings of Diesel engines, and judging by the results generally obtained in service its popularity is well deserved when compared with other materials used during the early part of this engine's existence. Close observation of these results over many years and in countless instances, however, suggests that rather less attention is given to its wear-resisting properties than is given to such matters as design to avoid fracture, and structure to ensure easy and accurate machining. The importance of these factors is fully realized, but in view of the widely different results obtained it would seem that greater attention could be given to its wear-resisting properties without sacrificing strength. Instances can be quoted where cylinder liner wear was negligible after twenty years, and in others the liners have had to be renewed after a quarter of that time. In one particular case the ship has traded for twenty-three years and the maximum wear of the greatest worn liner is 1.5 mm., whereas in another particular ship the wear after only twelve months is half that amount.

This is admittedly a complex problem and one that is outside the province of the engineer, but it is nevertheless felt that the development of materials of this class may be unnecessarily hampered by the shortcomings of foundry and, above all, machine-shop technique. That there are excellent wear-

resistant irons available to industry is well known, but difficulty in machining has hindered greatly their application. Wear-resistant cast iron, however, is so important to the shipowner that these difficulties should not be allowed to interfere with the desired properties of the finished article.

It is now recognized that resistance to wear in normal pearlitic gray iron is largely a function of structure rather than hardness, and that such structure may often be improved by small additions of alloying elements, such as nickel, chromium and molybdenum. There are, however, other cast-irons in use for applications involving wear resistance, which possess hard martensitic structures, and here would seem a field which might be explored more fully. Such structures can be obtained either by means of heat treatment or by alloy additions of nickel, chromium and certain other elements. Alloy additions offer, perhaps, the least difficulty, but if machining troubles are to be minimized the alternative method, namely heat treatment, could be carried out after machining providing the surface is finally ground.

These treatments do result, of course, in the development of high hardness throughout the section thickness, and it is only strictly necessary to produce high hardness in the surface layers. Largely for this reason, processes such as nitriding have been developed. This question of surface hardness is of considerable moment, and some food for thought is provided by the well-known fact that some pearlitic cast irons which rub or roll against similar material develop a very hard wear-resistant skin after a short "breaking-in" period. All cast irons, however, do not possess this property and as it sometimes occurs in parts which are not intended to resist wear and is occasionally absent in parts where resistance to wear is highly desirable, it would seem that either cooperation between the engineer and the metallurgist is not so close as it ought to be, or the foundry practices which result in a hard casting skin on certain cast irons are not fully understood or appreciated.

Reduction in rate of wear due solely to the polishing-down of the initial slight surface irregularities produced during machining would be expected, but the development of a hard skin implies a definite change in the character of the outer structure. This may be due to work hardening of the surface by plastic flow, or even the production of a partly transformed, martenistic structure. The possibility of some such surface change would go a long way to explain the exceptionally long life obtained with some engine cylinders. In this connection initial surface profile is important as it is often found that a smooth surface, produced by, say, grinding, develops a skin or glaze more rapidly than does a rougher surface.

Although one is led to believe that minor variations in composition are of far less importance than structure, it may be that surface oxidation of one or more of the elements present, for example, silicon, produces a skin of greatly increased resistance, not only to mechanical abrasion, but also to corrosion. Diagnosis of such changes in the outer layers of atoms and molecules would perhaps be the field of the practical physicist. If such changes were found to be responsible for enhanced wear resistance, then a lower limit might be desirable for, say, the silicon content, having in mind the C/Si ratio necessary to give the required structure in any given form.

Apart from considerations of mechanical abrasion, resistance to attack by corrosive elements is obviously of great interest today. In cases where this assumes importance, the use of the highly alloyed austenitic cast irons becomes a feasible proposition. Not only is the corrosion resistance of these materials of a very high order but resistance to

mechanical wear is also good. Here it would appear that although special foundry technique is called for, machining difficulties do not arise to anything like the extent they do in the case of the martensitic irons.

On the more general aspect of surface quality, wear is observed to decrease with decreasing roughness for purely mechanical reasons, but there is some reason to believe that there may be an optimum value beyond which it is unnecessary or even undesirable to go. Whether the important factor here is poorer retention of the lubricating film or the increasing degree of metallic bonding and pick-up between the mating surfaces, it is difficult to say.

## CYLINDER LUBRICATION

While it is advisable for cylinder liners and piston rings to be made of a material which has the highest possible wear-resisting properties, it is necessary to take all possible measures to prevent these parts from making actual contact by the formation and maintenance of an efficient oil film.

The formation and maintenance of an efficient oil film depends upon several factors, including the quality of the lubricating oil, the point of injection, the arrangements provided to distribute the oil and the exclusion of water from the cylinders. Moreover, if the desired results are to be obtained the maintenance of the oil film during inoperative periods must be given due consideration as there is little doubt that much liner and piston ring wear occurs during the first few hours after a period of idleness owing to inefficient lubrication.

The importance of using a high grade lubricating oil needs no emphasis because oil for cylinder lubrication has to do rather more than merely lubricate rubbing surfaces. It is exposed to extremely high temperatures and contamination from the products of combustion, fine particles of metal ground off cylinder liners and piston rings, and impurities entering the cylinder with the combustion air. Also it must not lose its lubricating qualities when a little water leaks into the cylinder from a defective connection in the cooling system. All oils will deteriorate under such conditions, but contamination of the nature mentioned results in the rapid deterioration of inferior oils and serious mechanical difficulties, in addition to excessive wear and tear of important parts. It is not possible to assess prior to use the capacity of any particular oil to resist oxidation and consequent deterioration when brought into contact with the products of combustion, so that it is wise to be cautious about using an oil which has not given good results under actual service conditions.

A cylinder oil that has proved satisfactory has the following physical properties:—

| | |
|---|---|
| Specific gravity at 60 deg. F. | 0.895 |
| Flash point (open), deg. F. | 500 |
| Pour point, deg. F. | 5 |
| Viscosity, Red. I at 140 deg. F., secs. | 425 |
| Viscosity, Red. I at 212 deg. F., sec. | 98 |
| Kinematic viscosity at 100 deg. F. (centistokes) | 360 |
| Coke No., Ramsbottom | 0.35 |

A continuous fluid film between the piston and cylinder is required, not only to prevent wear but also to maintain an effective gas seal between the moving piston rings and stationary liner. To establish and maintain an efficient film it is essential that the points at which the oil is injected should be correctly placed and sufficient in number, and that the oil should be of suitable viscosity. The viscosity must be high enough to enable the oil film to resist breakdown, yet not so high that the oil cannot spread evenly and easily over the cylinder walls. A further requirement is that the passage of oil through the working clearances and the proper functioning of the rings should not be hindered by asphaltenic, resinous or carbonaceous deposits. Formation of such matter in substantial quantity will most likely be due to incomplete combustion of the fuel. The lubricating oil is also, however, a possible source of such material, since the oil is spread in a thin film on metal at high temperature, and in the presence of burning gases to which more air has been supplied than is theoretically necessary to burn all the fuel. Consequently the oil is exposed to severe oxidation and some of it cannot escape combustion. Cylinder lubricating oil should, therefore, be sufficiently volatile to burn away cleanly, without forming excessive amounts of residue. Also it should possess high oxidation stability, so that it will not contribute to the accumulation of gummy deposits.

It is now generally agreed that in the case of single-acting engines the lubricating oil should be injected near the lower end of the cylinder, the position mostly favored being between the two uppermost piston rings when the crank is on bottom dead center. Attempts are sometimes made to inject at the moment the crank passes over this position, but it is extremely doubtful if this is achieved, as there is no discernible difference in the cylinder liner and piston ring wear or the amount of oil consumed when compared with similar engines in which the timing of injection is not attempted. As regards the distribution of the oil, satisfactory results are obtained when injection takes place at four equally spaced points in cylinders of from 25 to 30 inch diameter, and present-day lubricators can be relied upon to deliver regularly and consistently quantities as low as one-eighth of a gallon per 24 hours.

Observations made indicate that with the arrangements briefly outlined the great bulk of the oil finds its way between the piston rings and automatically spreads uniformly around the piston, but if the oil is to be put to the best possible use provision must be made to assist it to leave the annular spaces between the piston rings and build up a film on the cylinder liner. This is accomplished by rounding off the outer corners of the piston rings. Generally new rings are fitted or used rings re-fitted without troubling to round off the edges, and in many instances when this is considered advisable no real attempt is made to produce a uniform wedge-shaped clearance which will serve as a lead-in for the oil. If the oil is to be given the opportunity to do its work in preventing wear, the amount of metal removed should not only be substantial but the outer corners should be rounded and not merely rubbed off with a file the moment before a ring is fitted on the piston.

This is one of the reasons why it is considered unwise to make piston rings of comparatively soft material. If, as all will agree, the most effective way to reduce cylinder liner and piston ring wear is to produce and maintain an oil film of useful thickness between the rubbing surfaces, it is difficult to understand how this can result if after a few months' operation the outer corners of the piston rings regain their original sharpness and act as scrapers.

Generally speaking good attention is given to the factors which affect piston

ring and cylinder liner wear while an engine is running, but observations indicate that the importance of taking steps to maintain the oil film while the engine is being maneuvered and while at rest is not fully appreciated. When an engine is being started and stopped and operating at various speeds ahead and astern, the cylinder lubricators directly connected to the engine cannot be expected to deliver regularly and consistently. Moreover, moisture laden starting air being constantly admitted to the cylinders is not conducive to the maintenance of the film of oil between the rubbing surfaces. During such operations, therefore, the output of the cylinder lubricators should be greatly increased. In the usual type of lubricator no harm will result if the output is increased to the maximum, since in any case a small proportion only of the oil will find its way into the cylinder. In order that the rubbing surfaces will be left well coated with oil each crank in turn should be placed on bottom center and the respective cylinder lubricator operated by hand after the F.W.E. order has been received. The same procedure should be carried out prior to the engine being again put into operation and the quantity of oil injected reduced to the normal quantity only after the engine has attained normal speed and cylinder temperatures.

## CAUSES OF CYLINDER LINER WEAR

The amount and location of cylinder liner wear given earlier in this paper are typical of a very large number of four-cycle engines operating on fuels varying in viscosity from 40 to 3500 secs. Red. I at 100 deg. F., the notable features of which are:—

(1) The greatest wear takes place at the upper end of the cylinder and the least at the lower end.
(2) Generally the wear at the upper end is greatest in an athwartship direction.
(3) Wear at the lower end is also greatest in an athwartships direction but the percentage difference is less than at the upper end.

The reason why cylinder liners develop a tapered form is obviously due to the lubricating oil film at the upper end being thinner and less effective in keeping the rubbing surfaces apart than the film at the lower end. Also, if any abrasive matter results from the combustion of fuel or burning of lubricating oil its detrimental effect will be mostly shown at the upper or combustion end of the cylinder. The reason why the wear is generally greatest in an athwartship direction, however, is much less obvious. One view is that it is due to the reversal of pressure on the crosshead guides during each revolution, but as this phenomenon has been observed in engines with finely adjusted crosshead guides it is not very easy to accept such an explanation. Others hold the view that it is due to the lateral movement of the engine when a ship is rolling, but if this were so would not rubbing marks be clearly discernible on the corresponding parts of pistons?

On the other hand, the amount and location of the wear which has taken place in the cylinder liner of the experimental engine referred to later in this paper will be interesting. This engine, which has not, of course, been subjected to conditions produced by a rolling ship, had, when the gaugings given hereunder were taken, operated for 1400 hours at full power on fuels varying from 40 secs. to 3500 secs. viscosity. The original diameter of the liner was 25.591 inch and when gauged with more than usual care the figures obtained at the points indicated were as follows:—

| *Position* | *Fore and aft, inch* | *Athwartship, inch* |
|---|---|---|
| 4 inch down | 25.597 | 25.596 |
| Mid length | 25.597 | 25.596 |
| Bottom | 25.597 | 25.595 |
| Liner ext. top | 25.597 | 25.596 |
| Liner ext. middle | 25.598 | 25.597 |
| Liner ext. bottom | 25.600 | 25.600 |

For particulars regarding the position at which the measurements were made refer to Fig. 1.

Any investigation into the various causes of cylinder liner wear is rendered difficult by the great variation in the wear rates of exactly similar liners working under apparently identifical conditions. As a matter of fact recent experiments on liner wear carried out in America using laboratory apparatus and in which every factor was under good control gave results that showed appreciable variation, and the investigators concluded that "in actual engines where the conditions are under less control than in the wear test machine even greater variations in friction and wear may be expected." Nevertheless, there must be reasons for such variation, and as operating costs can be substantially reduced and conditions in the engine room made more congenial for the attendants by reducing the rate at which cylinder liners and piston rings wear, the matter deserves the careful consideration of all those with the facilities and knowledge and able to make a useful contribution to the solution of the problem. Particularly is this necessary at the present time in view not only of the greatly increased cost to supply new parts, but the longer time now taken to replace worn-out parts during periodical refit.

The engines which have provided the information on which the following remarks are based are all of the four-cycle single-acting, airless injection type, of 650 mm. bore and 1400 mm. stroke. The cylinder liner gaugings of fourteen engines have been analyzed at service periods of from 5000 to 20,000 hours operation; unfortunately in many cases the total number of full power hours' operation cannot be given as it was necessary during the war, for security reasons, to omit steaming time from deck and engine log books. However, it is known that all liners of each of the ships selected have been in use for the same number of hours, and this makes it possible to assess the differences between the liners of a particular engine.

In a ship with several years' service to its credit it is not unusual for the ratio of wear at the top of the most badly worn liner to the corresponding wear for the least worn liner to be as much as two to one, and the ratio of one-and-a-half to one is quite common. The reason for such wide variation in wear in a line of cylinders is not always apparent. Actually it may be more correct to say that in over 90 percent of cases the reason is obscure, since unequal wear takes place when all liners and piston rings are made of the same material and power developed and combustion efficiency the same in all cylinders and equal quantities of lubricating oil injected.

If the wear in one cylinder is greater than in another then there must be some difference in the conditions prevailing in each, and the cylinder in which the least wear occurs is the cylinder that is operating under normal conditions, assuming, of course, the wear rate in that cylinder to be not greater than 4/1000 inch per thousand full power hours. In all other cylinders forces which make for excessive wear are at work and if they could be located and eliminated in

time many years would be added to the life of the liners and much money saved in supplying and fitting new piston rings. Unfortunately such forces act silently and secretly and may be present in an engine which is operated and maintained in an exemplary manner in accordance with generally accepted standards. The conclusion reached, therefore, was that all the causes of excessive wear are not generally known and although the result of the investigation carried out and now about to be described clearly points to certain factors having a direct bearing on cylinder liner wear, it must be said that no claim is made to having discovered the complete answer to the reason why the wear in a line of cylinders operating to all outward appearances under exactly similar conditions should differ, but the observations recorded here might assist others who are interested in the solution of this problem.

A further matter for reflection, and one which is related to that mentioned above, is the manner in which wear occurs in the different parts of the same liner, and this was studied first in the hope that it would provide a clue to the solution of the major problem. It is well known that in all marine single-acting Diesel engines (leaving out of consideration opposed piston engines) wear occurs more rapidly at the upper end of the liner than at the lower end, for the reasons already given. Also, the admission of starting air, not always free from moisture, may contribute to the higher wear rate at the upper end. In the case of nine ships using Diesel fuel the average wear at the upper end of all liners to the average wear at the lower end was in the ratio of 2.2:1. In the *Auricula*, however, whose engines have operated on various grades of boiler fuel ever since she was built, this tendency to wear in a tapered form is less marked. The proportionately greater wear at the lower ends was most pronounced when the ship was new, and the ratio of wear at the upper end to the wear at the lower end has now stabilized at a figure of about 1.5:1. Recent cylinder liner gaugings of the four-cycle engines in the M.S. *Dromus*, which has been using boiler fuel since December 1948 but which for the previous ten years had used Diesel fuel, provide interesting corroboration of this fact. The wear ratio was 2.3:1 for the period on Diesel fuel and 2.1:1 for the subsequent twelve months' operation on heavy fuel, and judging from experience in other ships the ratio will be reduced as time goes on.

When cylinder liners wear in a tapered direction the conditions imposed on the piston rings, due to their having to follow the constantly varying diameter of the cylinder, are more severe than is the case with a parallel bore. Also, when new rings are fitted into a tapered cylinder liner the gap, or end clearance, must be governed by that necessary when the rings are in the lowest or least worn part of the cylinder, and this means that in the upper or high pressure part of the cylinder they are less effective as a gas seal. As the maximum wear rate is no greater when burning boiler fuels containing up to 3 percent of sulphur than when burning Diesel fuel, this peculiar feature when burning boiler fuel is not undesirable since it may well result in the piston rings giving longer service.

As to the cause of this unusual feature the following theory is put forward. With Diesel fuels, cylinder-liner wear is wholly due to abrasion, but when sulphur-containing fuels are used a proportion of the enlargement is due to corrosion. In the form of sulphurous fumes, which is the condition in the upper and hottest part of the cylinder, no detrimental effect will result from its presence, but when the rapidly cooling and expanding gases reach the lower and cooler end of the cylinder the $SO_3$ gas forms sulphuric acid ($H_2SO_4$), which condenses on and corrodes the lower

part of the cylinder wall. Most of this corrosion will take place when the engine is stopped or operating at comparatively low temperatures, such as when maneuvering in and out of port. The higher surface temperatures of the cylinder liners of the large slow speed marine engine, as compared with those of small high speed engines, due to the greater thickness of the liner material, make the former class of engine much less susceptible to the type of corrosion wear described, and it is unlikely that the wear resulting from this cause will ever exceed the maximum resulting from abrasion wear with fuels containing a much higher sulphur content than 3 percent.

A further noticeable feature in the engines which formed the basis for this analysis is that in almost all cases the liner wear in the athwartships direction is greater than that in the fore and aft direction, the ratios in the liners measured ranging from unity to 2.3, the average for the 112 liners gauged being 1.3. That is to say, the wear in an athwartship direction was 30 percent greater than in a fore and aft direction. This relationship was not affected to any noticeable extent by the grade of fuel used.

This ovality was not due to the side thrust of the pistons as a result of the ship rolling in a seaway. Had this been the case the greater wear in an athwartships direction would be caused by the corresponding part of the piston (for it could hardly be caused by the rings if they were free in their grooves) rubbing against the liner, and one would expect to find wear on the pistons corresponding with, and at least as great as, the wear on the liner. Careful examination of a large number of pistons failed to provide any evidence to support this theory. Moreover, if the bearing pressure between piston and liner due to the lateral component of the weight of the piston and piston rod produced by even so severe a condition as a permanent 20 deg. list is calculated, it will be found much too small (in comparison with the bearing pressures of the piston rings) to produce the observed athwartships wear on the liners.

It was therefore evident that some other explanation must be sought and accordingly a survey was made to determine the constructional differences of the engines in which the greatest and least wear athwartships occurred, and it was found that ovality does not occur in two-cycle opposed piston engines to any great extent. This type of engine, however, differs so widely from the four-cycle single-acting type that the number of possible explanations is not appreciably reduced by the fact that while the maximum wear rate is no less than in other types of engines, the athwartships wear is not appreciably greater than the wear in a fore and aft direction.

The liner gaugings for a number of four-cycle engines which differed from each other only in certain details were then examined and Table 4 compiled.

This brought out a significant fact, namely, that the engines which showed greatest ovality had their pistons cooled by water conveyed to and from them by telescopic pipes sliding in double glands similar to the arrangement shown in Figs. 1 and 4. The engines in which the least ovality occurred have their pistons either cooled by lubricating oil, or the water is conveyed to and from the pistons by a method which precludes any possibility of water splashing on to the liners. In some cases the cooling oil is conveyed to and from the pistons by telescopic pipes, but, as would be expected, any leakage past the stuffing boxes was not found to cause ovality.

Thus evidence points strongly towards the telescopic pipes as being responsible for the ovality in the liners of engines whose pistons are cooled by water, and the most reasonable explanation of excessive wear in an athwartships direction seems to be that small quantities of

TABLE 4

| Ship | Type of engine | Type of fuel | Method of piston cooling | Ratio of F. & A. to P. & S. wear at top of liners (mean of all cylinders) | Remarks |
|---|---|---|---|---|---|
| *Auricula* | Werkspoor 4 S.C.S.A. | HV | Water conveyed by telescopic pipes | 1 : 1·47 | All these engines have under-piston supercharge |
| *Lampania* | | HV | | 1 : 1·59 | |
| *Goldmouth* | | D | | 1 : 1·38 | |
| *Latia* | | D | | 1 : 1·19 | |
| *Neacra* | | D | | 1 : 1·28 | |
| *Turon* | M.A.N. 4 S.C.S.A. | HV | | 1 : 1·42 | |
| *Dromus* | B. & W. 4 S.C.S.A. | HV | | 1 : 1·13 | |
| *Nayadis* | B. & W. 4 S.C.S.A. | D | Oil | 1 : 0·94 | Supercharge by Buchi Blower |
| *Kellia* | Atlas-Polar 2 S.C.S.A. | D | Water conveyed up piston rod | 1 : 0·89 | |
| *Cerion* | Werkspoor 4 S.C.S.A. | D | Oil conveyed up piston rod | 1 : 1·0 | |
| *Latirus* | Werkspoor 4 S.C.S.A. | HV | | 1 : 0·79 | Under-piston supercharge |
| Experimental engine | Werkspoor 4 S.C.S.A. | HV | | 1 : 0·83 | |

water carried past the glands on the outside of the reciprocating conveying pipe during the up-stroke of the piston were being deposited on the part of the liner nearest the pipes, thereby decreasing the effectiveness of the lubricating oil film in that area. The position of the telescopic pipes of the engines in question is close to the starboard side of the liner, as shown in Fig. 1, and it is not unlikely that the air which rushes into the under-piston supercharge space during the up-stroke of the piston will tend to carry off any water on the pipes and deposit it on the part of the liner surface nearest to them.

The leakage of water through both parts of the gland when the packings become worn was known to occur, and if this was the cause of the ovality it follows that the wear in an athwartships direction would take place mostly on the starboard side of the liner, i.e., the side adjacent to the cooling water telescopic pipes. In order to find out if this

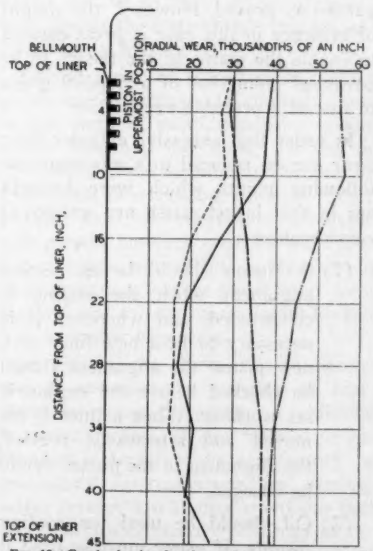



FIG. 10—*Graph showing location and extent of wear at all points of a Diesel engine cylinder liner*

was so a used liner was set up on a boring machine and readings taken with a dial indicator in a manner which would determine the amount of wear at seventy-two points of the liner's inner surface. The results for the forward, aft, port and starboard directions over the entire length are shown in Fig. 10. This test disclosed two noteworthy features, the first being that the athwartships wear was predominantly on the starboard side, or the side nearest to the piston cooling water telescopic pipes, and, secondly, that the wear approached parallelism along the length of the liner to a marked degree. This liner was from an engine that had been operating on boiler fuel.

In view of the erratic way in which different liners are affected by apparently similar conditions one must beware of concluding that a theory supported, however strongly, by the gauging of a single liner can be regarded as proved. However, the weight of evidence in this case is great enough to enable the status of the theory to be advanced from that of a hopeful guess to that of a probable explanation.

In order that excessive cylinder liner wear can be reduced to a minimum the following points which were brought out in this investigation are worthy of consideration:—

(1) A piston should be in perfect alignment when the engine is constructed, and whenever it is necessary to fit a new liner or a new piston the alignment should be checked before the engine is set working. When a liner is removed and afterwards refitted, the alignment of the piston should be checked.

(2) Oil should be used for cooling pistons. If water must be used it should be conveyed to and from the pistons by means that will preclude any possibility of water reaching the rubbing surfaces of liners.

(3) The lubricating oil must be of suitable quality and be injected regularly and consistently at a pressure which will avoid the oil being spurted beyond the surface of the liner.

(4) Distribution of oil should be assisted by the provision of oilways of suitable length and direction at each point of injection.

(5) Piston ring material should be the most suitable procurable and the upper rings should be renewed before the gap between the ends becomes so great that the gas pressure can build up behind them to any appreciable extent.

(6) Carbonaceous matter should not be allowed to accumulate at the bottom of piston ring grooves otherwise when new rings are fitted the outer surface of the rings may protrude beyond the surface of the piston and excessive wear result when the engine is started.

(7) Piston rings should be carefully sprung over pistons so that distortion during the process is reduced to a minimum and permanent set avoided.

(8) The quantity of lubricating oil injected should be greatly increased for a time before stopping and after re-starting an engine.

A possible but not very probable cause of greater wear in one particular cylinder is starting. It occasionally happens when maneuvering that an engine comes to rest with the crankshaft in such a position that one particular cylinder always receives the first charge of starting air, and when excessive wear is found in such instances it is probably

due to the oil film on the upper part of the liner's surface being adversely affected by the moisture in the air. Why some engines should stop always in the same position and the first charge of starting air contain more moisture than that which follows will not be debated here.

## POTASSIUM BICHROMATE IN COOLING WATER

It is customary at the present time to add to the fresh water used to cool pistons and cylinder jackets a small quantity of potassium bichromate, in order to prevent corrosion of metal parts. This chemical is a very efficient inhibitor when used in correct proportion. The amount to be added depends mainly upon the temperature and impurity content of the water. A rise in temperature calls for an increase in the amount of potassium bichromate needed to inhibit corrosion and it is roughly true to say that doubling of the temperature in degrees Centigrade will require doubling of the amount of bichromate needed. In the presence of salts such as chlorides and sulphates, which would almost certainly be present in the event of contamination by, say, sea-water, the amount of bichromate required is increased to an even greater extent. The effect of potassium bichromate on liner and piston ring wear in the event of any cooling water reaching these parts is, therefore, worth considering. The quantity of potassium bichromate in a small leakage of water may be almost microscopic, but no matter how small the amount which finds its way to the cylinder liners, it would probably continue to function as a corrosion inhibitor as long as it remained in solution, but ultimately, as it became more concentrated, it might revert to its solid form.

It is unlikely that the normal inhibiting action of potassium bichromate would be noticeable on the parts concerned with here on account of the higher temperature involved, and the possible presence of acid condensate. Indeed, it may be that corrosion would be accelerated in the presence of an appreciable concentration of acid, since it is known that under strongly acidic conditions chromates may act as cathodic stimulators. It is conceivable also that apart from its possible effect on the rate of corrosion, potassium bichromate, if present in solid form, may act as an abrasive, as the solubility of this compound in the oil film would presumably be very low. Although there is no evidence to support this possibility, it is reasonable to suppose that on the assumption that solid particles of potassium bichromate are present they will tend to increase abrasive action. This might be particularly so if decomposition of the potassium bichromate occurs with the formation of the well-known abrasive chromic oxide. Decomposition would not be expected to occur, however, unless the temperature reaches approximately 930 deg. F.

Consideration of the effect of adding potassium bichromate to cooling water in the event of small quantities of the water reaching the inner surface of cylinder liners was prompted by one or two liners overheating due to water leaking from piston cooling telescopic pipe glands. On each occasion the upper piston rings were found quite free in their grooves while the lower rings were jammed and in some cases found broken into a number of pieces.

In view of the above it is the intention to consider the question of inhibitors by means of soluble oil additions to cooling water. If this method of inhibition is found to be satisfactory in preventing corrosion in the cooling water system, it will also be obvious that any undesirable effect which may at the moment be connected with leakages of cooling water containing potassium bichromate will be eliminated.

## RESULTS WITH 3000 SECONDS FUEL

The price advantage when using fuels of a viscosity greater than 1500 secs. is relatively small, but until it could be definitely stated that the marine Diesel engine would operate satisfactorily on any fuel normally used under boilers, the author could not claim to have achieved his aim. It was therefore decided to continue the experiments with a view to covering the whole range of fuels used at sea, i.e., fuels having a viscosity of from 40 secs. to 6500 secs.

While, therefore, the *Auricula* and other ships were operating successfully at sea on 1500 secs. fuel, the only limitation imposed being that the fuel shipped did not have a viscosity greater than 1500 secs. Red. I at 100 deg. F., endeavors were made to burn 3000 secs. fuel in the experimental engine at St. Peter's Works, Newcastle-on-Tyne. It will be recalled that this experimental engine is an exact duplicate of one unit of a standard Werkspoor marine type supercharged four-cycle engine, the principal particulars of which are as follows:—

| | |
|---|---|
| Cylinder diameter | 650 mm. |
| Piston stroke | 1400 mm. |
| Revolutions per minute | 120 |
| Indicated horsepower | 500 |

Cylinder cooled by fresh water
Piston cooled by lubricating oil.
Airless fuel injection. Mechanically operated pump.
Under piston supercharge pump.

The first consignment of fuel received for the second stage of these experiments was found upon examination to have the following characteristics:—

| | |
|---|---|
| Specific gravity at 60 deg. F. | 0.971 |
| Flash point p.m. closed, deg. F. | 204 |
| Viscosity Red. I at 100 deg. F., sec. | 2260 |
| Sediment by extraction, percent weight | 0.08 |
| Water, percent vol. | 0.1 |
| Pour point, deg. F. | 15 |
| Ash, percent weight | 0.08 |
| Carbon residue (Conradson test), percent weight | 11.9 |
| Asphaltenes, percent weight | 7.6 |
| Sulphur, percent weight | 2.44 |

Although this fuel was less viscous than that requested it was decided to proceed with the tests. For the first run the fuel was purified at temperatures and in the manner which has been found most suitable for 1500 secs. fuel and no alterations were made to the engine, that is to say, the engine during the first test was adjusted for the burning of fuels ranging from 40 to 1500 secs. viscosity. The only difference was that in view of the higher viscosity of the fuel about to be tested it was decided to raise the temperature of the fuel at the moment of injection from 180 deg. F. (the most suitable temperature for 1500 secs. fuel) to 200 deg. F., so that the viscosity of the fuel as it entered the

cylinder would be about the same as, and the injection pressure of the 2260 secs. fuel not materially different from, that of the 1500 secs. fuel.

During the first test when the engine was run continuously for forty hours at approximately full power, the temperature of the fuel at the moment of injection fluctuated between 180 and 230 deg. F. owing to the method of regulating the heating steam not being satisfactory. Alterations were made to remedy this before the next test. When the fuel injection temperature was varying so widely it was observed that at temperatures between 220 and 230 deg. F. the running of the engine was somewhat erratic and that at a temperature of 230 deg. F. the engine speed was steadily less than the rated speed. The fuel in use was of the blended variety and the loss in speed was presumed to be due to the lighter constituents being vaporized and partially gasing the high-pressure fuel pump. This indicated that 200 deg. F. was about the limiting fuel injection temperature for engines of this make and that if the fuel injection pressure at this temperature was found to be too high other means would have to be found to avoid excessive injection pressures without sacrificing combustion efficiency.

For the next test a further consignment of fuel was received and the viscosity of this was found to be 3020 secs. Red. I at 100 deg. F. During this second test the engine was run continuously for forty-eight hours with an injection temperature of 200 deg. F., and although the engine operated regularly and to all outward appearances entirely satisfactorily, the data collected indicated that the combustion efficiency was below that obtained when operating on 1500 secs. viscosity fuel, but before endeavoring to improve the combustion efficiency by altering the fuel injection and/or atomizating devices it was decided to run further tests to determine beyond all doubt the correct injection temperature for fuel of this viscosity.

After a series of further tests had been run it was found that so far as the characteristics of 1500 and 3000 secs. fuel were concerned there was very little difference. In other words, the behavior of each inside the cylinder was much the same, providing, of course, that the 3000 secs. fuel was purified in the same way as the 1500 secs. fuel and given the necessary degree of atomization and penetration to ensure proper combustion of the fuel. During these tests the fuel valve nozzle in use was the one that had been found most suitable for 1500 secs. fuel when injected at a pressure of about 6000 lb. per sq. in. and a temperature of 180 deg. F. This nozzle had eight equally spaced holes of 0.85 mm. in the same plane and disposed in such a way as to give an angle of spray of 28 deg. to the horizontal.

When burning 3000 secs. fuel at 200 deg. F. with this nozzle in use the greater injection temperature reduced the viscosity of the fuel at the moment of injection sufficiently to avoid an increase in the injection pressure, but the combustion efficiency left much to be desired. The indications were that this was due to the fuel not being atomized sufficiently, with the result that the particles had not burnt completely before striking the confines of the combustion space. Ultimately the most suitable nozzle was found to be the one that had eight equally spaced holes of 0.75 mm. diameter.

Two tests of forty-eight hours each were then run, the first on 3000 secs. fuel and the second on a normal grade of Diesel fuel. The average hourly results obtained during each of these tests were as follows:—

| | *Diesel fuel* | *3020 sec. fuel* |
|---|---|---|
| Specific gravity at 60 deg. F. | 0.859 | 0.966 |
| Viscosity, secs. at 100 deg. F. | 45 | 3020 |
| Atmospheric temperature, deg. F. | 45 | 40 |
| Pressure at h.p. pump suction, lb. per sq. in. | 25 | 25 |
| Temperature h.p. pump suction, deg. F. | 65 | 200 |
| Fuel viscosity at above temperatures | 88 | 255 |
| Fuel injection pressure, lb. per sq. in. | 4400 | 6150 |
| Supercharge air pressure, lb. per sq. in. | 5.5 | 5.5 |
| Supercharge air temperature, deg. F. | 120 | 112 |
| Exhaust gas temperature, deg. C. | 347 | 325 |
| Fuel lever position | 17¼ | 16½ |
| Fuel consumption per b.h.p.-hr. | 0.453 | 0.465 |
| Revolutions per minute | 120 | 120 |
| Cylinder compression pressure, lb. per sq. in. | 526 | 522 |
| Cylinder combustion pressure, lb. per sq. in. | 695 | 760 |
| Mean indicated pressure, lb. per sq. in. | 130 | 135 |
| Indicated horsepower | 559 | 579 |

It will be observed that a moderately high pressure is maintained at the fuel pump suction. It is standard Werkspoor practice to employ a surcharge pump for this purpose and the practice was not varied throughout these fuel experiments. Nor were tests undertaken to find out if a lower pressure would suffice. It doubtless would in the case of Diesel fuel, but for viscous fuels an adequate pressure at the fuel pump suction to ensure the fuel following up the plunger is considered advisable.

When operating on 3020 secs. fuel the speed control lever had to be retarded from notch 17¼ to notch 16½ in order to keep the speed at 120 r.p.m. The reason for this was the higher specific gravity of the heavy fuel, resulting in a greater weight being delivered by each stroke of the high pressure pump. The effect of the difference in the calorific value, i.e., 19,200 B.Th.U. for the Diesel fuel and 18,510 B.Th.U. for the 3020 secs. fuel, would have been to cause the lever to be advanced in order to maintain the speed, but the greater heat in the heavier charge of fuel out-weighed the higher calorific value of Diesel fuel.

Owing to the high viscosity fuel having a slower burning rate than Diesel fuel it is necessary to begin injection of fuel earlier if the pressure rise upon injection of fuel is to be maintained. In this particular test this was slightly overdue since the pressure rise was increased by 65 lb. per sq. in.

The exhaust temperatures, it will be observed, are slightly different. This is accounted for to a certain extent by the higher atmospheric and supercharge air temperatures prevailing during the test on Diesel fuel. As regards the appearance of the exhaust gases there was no noticeable difference, a slight haze only being visible during each test, while the beat of the engine and the sound of the exhaust were definitely better when running on the higher viscosity fuel.

So far as full power operation was concerned the results obtained during these tests were considered sufficiently satisfactory to make a test under service conditions, but before doing so, a half-power test of forty-eight hours' duration was run to see what effect reduced power operation would have upon the fuel valve nozzles. The first ship selected

to burn this grade of fuel was the M.S. *Auricula,* whose chief engineer was making his first voyage burning boiler fuel. The bunkers shipped had a viscosity of 2920 secs. Red. I at 100 deg. F. and the following is the chief engineer's record of the voyage.

The ship left the berth at Curaçao burning 1500 secs. fuel and after passing outside the islands the engine was stopped to fit the new fuel valve nozzles, after which the engine was re-started and changed over to the more viscous fuel, which was injected at a temperature of 192 deg. F. The injection pressures at this temperature varied between 6500 and 7000 lb. per sq. in. The temperature of the fuel was lowered to 180 deg. F. but the exhaust became visible and the temperature was again raised to 190-200 deg. F.

During the passage to Dover very heavy weather was encountered and when the sea temperature fell to 65 deg. F. it became necessary to heat the fuel in the cross-bunker to 90 deg. F., at which temperature the 40-ton capacity pump could transfer the fuel at the rate of 20 tons an hour. The purifier and clarifier were run for eleven hours each day and the former extracted 21 lb., 2 oz. of matter and the latter 12 oz. from each day's supply of 13½ tons.

After running most satisfactorily for 10 days on 2920 secs. fuel the engine was stopped to examine Nos. 4 and 5 fuel valve nozzles, which were found in perfectly clean condition. The weather having moderated somewhat the engine was run ahead and astern at varying speeds for a few minutes, and responded perfectly. A few days later when the weather had moderated sufficiently to allow the engine to run steadily at 116 r.p.m., the indicator diagrams attached (see Fig. 11) were taken. The performance particulars at that time were as follows:—

| | |
|---|---|
| Air temperature | 42 deg. F. |
| Sea temperature | 46 deg. F. |
| Fuel injection temperature | 190 deg. F. |
| Fuel injection pressure, average | 6815lb. per sq. in. |
| Mean effective pressure, average | 125.2lb. per sq. in. |
| Total i.h.p. | 4155.8 |
| Daily fuel consumption | 13.4 tons |
| Fuel consumption per i.h.p.-hr. | 0.3lb. |
| Ship's speed | 11.83 knots |
| Propeller slip | 11.7 percent |

This ship entered the Baltic through the Kiel Canal and proceeded to Turku and afterwards Helsinki. The engine movements through the Canal and at the ports mentioned totaled 469, of which 147 were starts from stop. On one occasion three hours elapsed between one stop and the next movement, during which the only means adopted to keep the fuel at the desired temperature was to circulate the fuel valve jackets with water at 140 deg. F. When the engine was put slow ahead the injection pressure recorded was 7500 lb. per sq. in. but this pressure quickly fell to 4500 lb. per sq. in. at 45 r.p.m.

Upon arrival at Helsinki certain parts of the engine were opened up for examination and their condition found to be as follows:—

*No. 4 Air Inlet Valve.* Condition clean, faces good.

*No. 4 Exhaust Valve.* Faces good. slight yellow deposit on lower end of spindle and upper surface of lid.

*No. 4 Fuel Valve.* Slight deposit on exhaust valve side of nozzle. All holes quite clear.

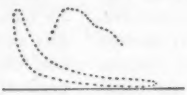
M.V. *Auricula* loaded ship Curaçao to Finland 15.11.49
M.i.p. 125·2. I.h.p. 4155·8. R.p.m. 116. Supercharge pressure 6·3. Air temperature 42 deg. F. Sea temperature 46 deg. F. Engine room temperature 81 deg. F. Light wind and sea N.N.W., force 2. Curaçao fuel specific gravity 0·966. Fuel control lever 13½. Viscosity Redwood I at 900 deg. F. 2,920. Scale 1/500. Speed 11·83 knots. Slip 11·7.

*Cylinder No. 1*
M.i.p 123; fuel injection pressure 6,800; exhaust temperature 310 deg. C.; compression 555; max. pressure 715; i.h.p. 510·4.

*Cylinder No. 2*
M.i.p. 125; fuel injection pressure 6,600, exhaust temperature 312 deg. C.; compression 560; max. pressure 730; i.h.p. 518·7.

*Cylinder No. 3*
M.i.p. 122·5; fuel injection pressure 6,830; exhaust temperature 310 deg. C.; compression 565; max. pressure 725; i.h.p. 508·3.

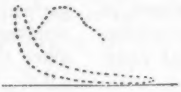
*Cylinder No. 4*
M.i.p. 126, fuel injection pressure 7,000; exhaust temperature 312 deg. C.; compression 560; max. pressure 730; i.h.p. 522·9.



*Cylinder No. 5*
M.i.p. 126·5; fuel injection pressure 6,800; exhaust temperature 315 deg. C.; compression 555; max. pressure 725; i.h.p. 524·9.

*Cylinder No. 6*
M.i.p. 126·5; fuel injection pressure 6,900; exhaust temperature 308 deg. C.; compression 555; max. pressure 725; i.h.p. 524·9.

*Cylinder No. 7*
M.i.p. 127; fuel injection pressure 6,800; exhaust temperature 315 deg. C.; compression 545; max. pressure 725; i.h.p. 527.



*Cylinder No. 8*
M.i.p. 125, fuel injection pressure 6,800; exhaust temperature 310 deg. C.; compression 540; max. pressure 730; i.h.p. 518·7.

FIG. 11—*Indicator diagrams from* Auricula *when operating on 2,920 sec. fuel*

*No. 4 Piston.* Crown clean. Faint yellowish marks indicating fuel sprays. All rings free. Slight deposit above rings.

*No. 4 Cylinder Liner.* Well oiled, smooth and bright.

*Supercharge Spaces.* All clean except Nos. 3 and 6, in which a small amount of sludge was present.

*Supercharge Valves.* Dirty but all working freely.

*Crankcase Oil.* Dark in color but appears good.

This was the condition of the parts after the engine had operated for 433 full power hours on 2920 secs. fuel and a very much longer period on 1500 secs. fuel. To obtain the total length of time in service reference will have to be made to the period in use prior to the periodical drydocking at Cardiff in August 1949.

After all parts had been refitted and the cargo discharged the *Auricula* began her second voyage on 2920 secs. fuel with instructions to accept in future any fuel offered so long as the viscosity did not exceed 3500 secs. Red. I at 100 deg. F.

## PURIFICATION OF BOILER FUELS

The successful outcome of these Diesel engine fuel experiments is mainly due to (a) the extraction of a high proportion of the ash-forming constituents before the fuel is injected into the engine cylinders; (b) injection at a temperature which reduces the viscosity and makes the fuel more easily atomized, and (c) determining the alterations necessary to the fuel injection system in order to avoid too great an increase in the injection pressure. As the aim was to burn boiler fuels in existing engines without having to carry out any major alterations, the combustion efficiency usual with this type of engine

had to be obtained without any appreciable increase in the fuel injection pressure, and so obviate too great a strain being put upon the fuel pump driving mechanism.

The fuel treatment, as is now generally known, is to heat the fuel to 180 deg. F. before it passed through a centrifugal separator known as the "purifier," and then through a second centrifugal separator known as the "clarifier." The principal difference between these separators is that the bowl of the purifier is designed to effect the separation and discharge of water as well as the coarser particles of mineral matter present in varying degree in all high viscosity fuels. The purifier has two outlets, one for the ejection of the mineral matter and water, and the other for the purified fuel, whereas the clarifier has one outlet only, through which the clarified fuel is discharged. The latter machine, therefore, retains the separated matter. The quantity of solid matter extracted by the clarifier, however, is small and the capacity of the dirt space in the bowl so large in comparison that opening-up for removal of the extracted matter only requires to be done at infrequent intervals. In the size of purifier and clarifier used the bowl dirt space will collect about 20 lb. of matter before its efficiency is adversely affected. The extraction is about 2 lb. in the case of the purifier and 6 oz. in the case of the clarifier for every ton of fuel treated. It will be appreciated that the amount of matter extracted by either machine, and the frequency with which the bowls require to be cleaned, is influenced by the composition of the fuel, and the quantity and nature of the mineral matter picked up by the fuel before it reaches the ship's bunkers.

As, however, the best all-around results in ship operation in the circumstances which exist today are achieved by reducing as far as possible the amount of manual work, particularly if it is not of a congenial nature, to be done by the engine-room staff, it would be an advantage if one centrifugal separator could be devised to give the necessary degree of purification. A further advantage would accrue if this machine could be made self-cleaning, and so obviate having to remove the bowl for cleaning purposes. The paramount consideration, however, is maximum extraction of the ash content of the fuel treated and the bowls must be made self-cleaning without affecting this quality in any way if satisfactory operation of an engine running on normal grades of boiler fuel is to be obtained.

With regard to the satisfactory performance of centrifugal separators it is not possible to determine accurately by analysis the suitability of the fuel after treatment. For instance, many treated and untreated samples examined in the laboratory do not disclose any significant difference in characteristics, yet some change must have taken place because the black, sticky matter extracted during the purification process can be collected, weighed and analyzed. Moreover, whenever an attempt has been made to operate an engine on such fuel without first treating in the manner recommended here the results obtained were greatly inferior to those obtained with purified fuel, proving that while the routine commercial methods of analysis disclose no significant alteration during treatment, matter injurious to the engine must have been extracted during the process. It would seem, therefore, that before the suitability of centrifugal separators can be compared, more accurate methods of analyzing samples before and after treatment than is at present practiced will require to be found and adopted. A better guide would be to measure the quantity of matter extracted for a given quantity of fuel treated and find by analyses the composition of the matter extracted.

The procedure followed in these ex-

periments was:—(1) to ascertain which of the constituents of boiler fuel were detrimental to the Diesel engine; (2) to determine how the objectionable constituents could be removed, and (3) find out how high viscosity fuel freed from the injurious constituents could be burnt efficiently without effecting major alterations to existing engines. It was generally recognized that the usual high content of ash-forming constituents of such fuels, or of any fuels for that matter, was exceedingly injurious and resulted in excessive wear of cylinder liners and piston rings. Sulphur was believed to have a serious corroding effect upon exhaust valves and the metals surrounding the exhaust gas passages, while a high Conradson value was considered responsible for accumulation of carbonaceous matter in cylinders and on fuel injection valve nozzles. It was also assumed that such viscous fuel could not be atomized sufficiently to insure it burning completely in the short time allotted to the process.

Tests carried out with the experimental engine indicated, and results obtained in service have since proved beyond all doubt, that ash is the only injurious constituent, that while sulphur may not be a desirable constituent its corrosive effect has been greatly exaggerated and is a negligible quantity in marine engines, that a high Conradson value does not result in choked fuel spray nozzles and that such viscous fuels can be burnt completely in slow running marine engines.

The nature of the ash-forming constituents extracted is rather complex, and this is not surprising when it is remembered that it is representative of a very large quantity of fuel and that such constituents which are normally recognized as traces in petroleum will appear in measurable quantities in the extracted matter. Analysis of the ash has disclosed oxides of the elements silicon, iron, aluminum, calcium, magnesium, sodium, copper, lead, barium, titanium, vanadium and manganese. The sodium is present as chloride and sulphate and it is probable that these are derived from sea water contamination, but most of the other constituents are from the fuel itself.

So far it has not been possible to extract more than about 50 percent of the ash content of boiler fuels, but endeavors to increase the proportion extracted are continuing. The quantity of ash in a sample of fuel examined is so minute—the average amount is 0.06 percent—that it is not surprising that the proportion removed is difficult to determine when comparing treated and untreated samples. It may well be that this is the reason why earlier investigators did not succeed in operating the Diesel engine on fuels having a relatively high ash content. If, for instance, it was recognized that excessive wear of vital parts and carbonizing of the fuel valve nozzles were due to the ash content and analysis proved, as it might well do, that treatment effected no change, such treatment would be considered superfluous. Nevertheless, even though the quantity of ash extracted by the method recommended here is so small, its extraction is vital if an engine is to operate satisfactorily on boiler fuels. This will be appreciated when it is stated that the 9009 tons of fuel burnt by the *Auricula's* engine during the first three years' service contained before treatment approximately 5.40 tons of ash. After treatment the ash content is halved and brought more nearly in line with the average ash content of Diesel fuel.

The reason why the ash content of such fuels is reduced by some 50 percent only is that the mineral matter present as assessed by an ash determination is derived from two sources, one being organic and the other inorganic. The organic compounds of metals are in an oil soluble form and one is told that these cannot be extracted by the centrifugal separators as at present constructed and operated, but something

may come of the work now in hand to effect this. The inorganic portion of the ash consists chiefly of tank scale, silica and other matter, much of which is in colloidal form. The larger particles can be extracted either by settling over a long period or centrifuging in the ordinary way, but the portion in colloidal form can be extracted only by distillation or subjection to centrifugal force of an unusually high order.

In all previous attempts to burn boiler fuels in Diesel engines the practice was to heat the fuel to about 100 deg. F. and pass it through a centrifugal separator at the maker's rated throughput, after which it was injected into the engine cylinders at from 100 to 200 deg. F. So far as is known the results obtained were never published, but one shipping company in this country who made a methodical investigation into the problem and who probably achieved more success than any of the others, has recorded that when compared with the results obtained with Diesel fuel the cylinder liner wear rate increased 400 percent and constant trouble was experienced with the exhaust valves burning. As the wear rate of liners is no greater and exhaust valves give even less trouble when the boiler fuel is treated as recommended here, and as it is claimed that the insoluble portion of the ash content only is extracted it would appear that it is this portion which is mainly responsible for the greater liner wear and exhaust valve trouble when such fuels are not specially treated before being injected into the engine cylinders. In other words, it is the inorganic rather than the organic matter in high viscosity fuels which causes the differences in the results obtained when operating an engine on normal marine Diesel fuel as compared with unpurified boiler fuel.

This is not to say that there is no advantage to be gained by the extraction of the organic portion of the ash if this were possible by commercially practical means. On the contrary, results obtained in the experiments conducted during the past few years suggest that if the whole of the ash content could be extracted from high viscosity fuel before it is introduced into the engine cylinder, the wear of vital parts would be very much less than when burning Diesel fuel. The reasoning behind this statement is that from close observations made it is evident that although the heat contained in boiler fuel is released within the allotted time, its rate of release is comparatively slow when compared with Diesel fuel. One proof of this is that when changing over to Diesel fuel after running on the boiler fuel, the pressure rise upon injection increases by approximately 30 lb. per sq. in. As, therefore, the heat in boiler fuel is released at a slower rate there will be less concentration of heat at the upper end of the cylinder and the oil film on that part of the liner will be scorched to a lesser extent than with Diesel fuel. This being so, the problem of maintaining an efficient oil film over the upper part of the liner's surface should be less difficult, and if the ash content of boiler fuel can be reduced to that of Diesel fuel it is reasonable to expect that, all other conditions which affect wear being equal, the cylinder liner and piston ring wear rates should be less when using boiler fuel than when using Diesel fuel.

The reason why high viscosity petroleum contains more inorganic matter than low viscosity fuels, such as Diesel fuel, is not difficult to understand when it is remembered that the more viscous fuel will more readily pick up such matter, and in view of its relatively high specific gravity it is more difficult to remove. As fuels with a viscosity of 300 sec. Red. I at 100 deg. F. and over have hitherto been used mainly for steam raising in boilers where freedom from inorganic matter is not so important, no particular attention has been given to its exclusion, but now that such

fuels are being used for internal combustion engines greater care should be taken to avoid contamination, both in the refinery and during its journey to a ship's bunker tanks. Even the greatest care possible will not eliminate the necessity to purify the fuel on board before it reaches the engine, but it will result in less frequent cleaning of the centrifugal separator bowls.

Since these experiments began innumerable tests have been carried out to determine the best purifying temperature, and although the early tests indicated that a satisfactory temperature was around 180 deg. F. it was decided to carry out specially careful tests at 100 deg. F., 140 deg. F. and 180 deg. F. before proceeding with the extended experiments which had for their purpose the burning of fuels having a viscosity greater than 1500 secs. Red. I at 100 deg. F. A temperature higher than 180 deg. F. was not considered advisable because of the evaporation of the lighter hydro-carbon mixtures during the purifying process. The results of these tests can be summarized as follows:—

(1) Raising the temperature had the effect of increasing the amount of matter extracted by the purifier and the clarifier also, but in the case of the purifier the advantage was not so pronounced above 140 deg. F., whilst in the case of the clarifier the advantage was more pronounced above that temperature.

(2) The viscosity and the flash point increased very slightly after passing through both the purifier and clarifier due, presumably, to a slight loss of the lighter fractions as a result of pre-heating.

(3) The sulphur content was not affected in the least degree by passing through either the purifier or the clarifier at any temperature.

(4) The whole of the water and a portion of the salts were extracted by the purifier and a further but lesser portion of the salts was extracted by the clarifier at temperatures above 140 deg. F.

(5) Raising the temperature of the fuel had the effect of removing proportionately greater quantities of the asphaltenes.

(6) The ash content was reduced by the purifier and further reduced by the clarifier as the temperature was increased.

Samples of treated and untreated fuels, together with samples of extracted matter, were examined by petroleum technologists, who reported as follows:—

"It is confirmed that the major portion of the total ash content extracted during treatment was insoluble inorganic matter. The bulk, comprising particles of silica, alumina and iron oxide being removed by the purifier, and a smaller portion by the clarifier. Other compounds extracted were calcium and sodium oxide, chlorides and some sulphur compounds, such as sulphates. Examination of the matter extracted by both the purifier and the clarifier disclosed that the major elements comprised iron and calcium, the average size of the particles being 5 microns (a micron is 0.001 mm.). Aluminum and silicon were also present.

A factor that may be of some interest is the size of the particles extracted from the sludge. The increase in maximum size with temperature would appear merely to indicate greater coagulation during centrifuging. However, it would seem clear that particles of the 5 microns size or even larger may be present in the oil prior to centrifuging. If these approach, say, 50 microns combustion might not be really complete and this may contribute to engine deposit trouble unless removed by the centrifuging process. It is considered that the particles observed under the microscope, while appearing carbonaceous, probably

contain the silica and iron oxide particles as hard central cores.

After studying the analytical figures supplied our impression is that when accurate determinations are practicable, it is certainly possible to detect, after centrifuging, differences in the chemical constituents of fuel oil. It is considered, however, that greater reliance could probably be attached to the composition and constitution of the sludges rather than of the oil, as these have been shown without question to contain far greater and more easily determinable percentages of some deleterious constituents than does the original oil. In some cases analysis of the oil has, of course, shown quite clearly that it has undergone a significant change, but where this is not disclosed by the analytical figures it is probably because the samples on which the laboratory tests were made were very small."

Upon looking back it would seem that the Diesel engine would not have survived had the petroleum industry not been quick to appreciate the advantages of the compression ignition engine and produced a fuel commonly called Diesel fuel, which would enable the engine to operate reasonably free from troubles accruing from imperfect combustion. One of the requirements was that the fuel should not contain appreciable quantities of sulphur, because this constituent was held responsible for excessive cylinder liner wear and corroded exhaust valves and exhaust gas passages. There is no doubt that the imposition of this restriction was justified by results, as were the limitations imposed on viscosity, Conradson carbon content, etc.

As time went on engines became larger, and when this type of engine was adopted for ship propulsion rotational speeds became slower. Many important features of the engine were altered until Dr. Diesel himself would have found difficulty in recognizing the engine he had invented. This high compression engine, however, continued to be supplied with Diesel fuel, and in spite of the increase in the size of the engines and the improvements introduced, fuel specifications remained very much the same. Even now some consumers are inclined to demand a sulphur-free fuel, while there are still manufacturers of Diesel engines who are unwilling to accept liability for damage done to their products during the guarantee period if the fuel contains more than 1.0 percent sulphur.

The author has been associated with marine Diesel engines for thirty-five years and while yellow colored substances have been observed on exhaust valve stems and in exhaust gas passages, in no instance have the metal parts in contact with the burning fuel or the burnt gases been found corroded in a way which could, even with a wide stretch of the imagination, be attributed to sulphur in the fuel. Generally, the yellow substances referred to was much too small in quantity to enable an analysis to be carried out but on one occasion when burning 1500 secs. fuel containing 2½ percent of sulphur in the *Auricula* one of the joints on the exhaust manifold began to leak and a sulphur-like substance deposited on the lagging near the leak. Judging by the appearance and knowing that the fuel in use contained 2½ percent sulphur it would have been difficult to convince many that the yellow substance was not sulphur. Fortunately the quantity was sufficient to enable an analysis to be carried out and this disclosed that the substance did not contain even a trace of free sulphur, it being composed of vanadium pentoxide $V_2O_5$, which is yellow in color, traces of soluble sulphate and a very small quantity of sulphuric acid. The report on this examination concluded with the statement that the results of this analysis indicated normal combustion conditions.

Whilst much has been heard during the last thirty-five years about the injurious effect of sulphur in fuel, and this constituent has times without number been blamed for exhaust valves burning and piston rings leaking—on one occasion a shipping company in all seriousness claimed the replacement of a broken piston rod because of the alleged inferior quality of the fuel—it is questionable if evidence could be submitted which would prove that sulphur in fuel was responsible for any damage, with the possible exception of corrosion of finished steel surfaces in the crankcase. There is a certain amount of evidence that the products of combustion from sulphur-containing fuels do find their way into crankcases and, by reacting with the salty atmosphere, produce a corrosive effect on the crankpins and journals of certain two-cycle engines, but surely it is not beyond the capacity of engine builders to provide means which would prevent the bearing oil being contaminated in this way.

The reason for the fairly widespread objection to sulphur in marine Diesel engine fuels is hard to find unless it is that those who hold such views overlook the fact that as engines got bigger cylinder liners became thicker, and that while the early relatively small high-speed engines did suffer from sulphur in the fuel, it was because their cylinder liners were much thinner than those of present-day marine engines and consequently the inner surface had a much lower operating temperature. Experience suggests that sulphur has a detrimental effect upon certain types of present-day high-speed engines, but fortunately for the shipping industry large slow-speed Diesel engines are much less susceptible to sulphur in their fuel. The reason for this is that the heat transfer to the surrounding cooling water is consequently less than in the case of engines having relatively thin cylinder liners. There being less heat transfer in a thick liner, the normal running temperature of the inner surface is appreciably higher and the formation of corroding sulphuric acid cannot occur under normal full load conditions.

In the past the petroleum industry has been able to supply the shipping industry with Diesel fuel of relatively low sulphur content, generally speaking, below 1.8 percent. There is no immediate indication that this state of affairs will change, but it must be realized that there is a rapidly increasing demand for the lighter Diesel fuel components, as a result of the introduction of Diesel propulsion in rail and road transport and agriculture. For example, the American railways are enormous consumers of distillate Diesel fuel; in 1949 they consumed 30 times as much as in 1939, and of the locomotives now being constructed in the U.S.A. 90 percent will be of Diesel-electric type. It is not possible to say yet whether this increasing demand for the lighter Diesel grades will affect those used for marine Diesel purposes, but, at any rate, it does seem fairly evident that there will be no appreciable diminution in the sulphur content of marine Diesel fuels.

It is possible to extract sulphur from the fuel before it leaves the refinery, but the cost of doing so would be prohibitive. Shipping companies, however, need not be concerned about this, because the *Auricula* and many other ships have been operating for years on fuels with up to 3.0 percent sulphur, and in no instance has any part of the engines suffered. In view of the results obtained with these ships the author would have no hesitation in accepting fuel with a sulphur content up to 5 percent or even higher, were it not that the higher the sulphur content the lower the caloric value of the whole.

## CAUSES OF CARBON FORMING ON FUEL VALVE NOZZLES

The serious consequences of incomplete combustion of fuel in oil engines are well known. Apart from a greater quantity of fuel being required to produce a given power output under such conditions, mechanical difficulties arise, such as the accumulation of partially burnt carbon in the cylinders, fouling of piston rings and contamination of crankcase lubricating oil, resulting in crankshaft mal-alignment. If such a condition is allowed to continue the position becomes rapidly worse and ultimately cylinder liners and piston rings will require to be replaced by new parts and the bearings re-metalled. The excessive wear in the bearings arises from carbonaceous matter in the crankcase lubricating oil, the presence of such matter in the lubricating oil is mainly the result of ineffective piston rings, and piston rings become ineffective and cylinder liners wear excessively because carbonaceous matter from the combustion space finds its way between these two parts, and such matter is produced in the combustion space because the fuel is not wholly converted into gas.

In some instances the matter resulting from incomplete combustion found in the combustion chamber end of cylinders is soft and feels smooth when rubbed between the fingers, while in others it is hard and has a gritty feel. The soft kind of deposit generally results when burning wholly distilled fuels. The hard, gritty variety is produced when residual fuels or blended Diesel fuels, i.e., a mixture of gas oil and residual fuel, are improperly burnt, and unless the fault is remedied the solid matter resulting therefrom will rapidly accumulate until the serious state of affairs just described is reached.

Generally, although not always, the sequence of events in the formation of solid matter in the cylinders and on piston crowns is that either a coke- or carbon-like substance first forms on the fuel injection valve nozzles. As time goes on this substance increases in bulk and ultimately the direction of the fuel sprays, or the angle of the sprays, is altered. When this occurs the position deteriorates very rapidly. It would seem, therefore, that in most instances, providing the grade of fuel is not unsuitable for a particular engine because of some unusual feature and that the fuel injection devices of the engine are in proper order, the accumulation of solid matter in the cylinders and the consequential ill effects would be avoided if building-up of deposit on the fuel valve nozzles could be prevented.

In a few instances the accumulation of deposit on fuel valve nozzles is started by the presence of solid matter in one or more of the spray holes altering the direction or angle of the sprays. This obstruction may be caused by a piece of grit just too large to pass through a spray hole, or to the working temperature of the fuel valve spray nozzle being so high that the small portion of the fuel making contact with the sides of the holes is carbonized as it passes through the nozzles. In the latter event the spray holes will become lined with carbon and eventually choke. Before choking occurs the deposit begins to accumulate on the cylinder side of the nozzles. The reason for this is that as the spray holes become lined with carbon their cross-sectional area is reduced and the resistance to the flow of the fuel consequently increased. This affects the degrees of atomization and penetration to the point where the light-weight fuel particles ignite so close to the nozzle that some of them begin burning in an insufficient quantity of air and, being starved of oxygen, partially burnt fuel is deposited on the nozzle and the parts surrounding it.

Most frequently, however, the accumulation of deposit begins on the

outside of the nozzles in close proximity to, but not in, the spray holes, and is due to incorrect angle of spray, too low an injection pressure, needle valves not perfectly fluid-tight, sluggish action of needle valve, or needle valve shrouded. Enlarged spray holes are rarely the cause of deposit accumulating on the nozzles. Such a fault does, however, result in deposits on other parts surrounding the combustion chamber, such as the top of the piston and the confines of the cylinder.

A condition necessary to insure complete combustion of fuel in oil engines, irrespective of the grade of fuel used, is that the fuel be atomized to a degree that will enable every particle to be burnt in the short space of time allowed and that the particles be evenly distributed throughout the combustion air. Also, the fuel particles must be gasified before they make contact with any metal surface surrounding the burning fuel, since should a metal surface be contacted the fuel will become de-atomized, in which condition its combustion rate is greatly reduced and it will not burn completely in the time allowed. This is what happens when deposition occurs on the piston crown and around the combustion space of a cylinder and no such deposit is found on the fuel valve nozzle. Such a state results from the fuel not being atomized sufficiently and the comparatively large particles are consequently driven too far, thereby making contact with metal surfaces before they have burnt completely. Enlargement of spray holes produces such a state.

The substance which deposits on fuel valve nozzles is of two distinct varieties. One is decidedly black, has a plumbago-like structure and can be easily ground to a smooth powder between the fingers. The other variety is black, has a coke-like structure and whilst it can be ground between the fingers the resulting powder is gritty. The cause of the deposit is probably the same in each case, namely that the entire fuel charge is not injected into the cylinder with the requisite force. The plumbago-like substance, however, as mentioned earlier, occurs only with distilled Diesel fuel and accumulation will continue until the fuel valve is taken out and the deposit removed by hand. The coke-like deposit, on the other hand, accumulates and then breaks off or burns away before it has reached dimensions great enough to interfere with the fuel sprays.

When high viscosity fuels are not injected with the requisite force, the deposit generally found on fuel valve nozzles is of the coke-like variety which is the least objectionable of the two because it can be completely burnt off by changing over to Diesel fuel without stopping the engine and running for half-an-hour or so on this grade of fuel. When, however, all parts of the fuel injection system are in good order it has been found that deposit occurs only when the engine is running at greatly reduced power output for long periods, and that when the engine is again put on full power the deposit disappears. Accumulation is gradual and the burning-off takes place rapidly. On numerous tests carried out it was found that the accumulation after eight hours half full power operation was not sufficient to interfere in any way with the fuel sprays and that the spray nozzles were freed entirely of the accumulation after half-an-hour at full power on the same grade of fuel.

The bulk of the deposit which occurs whilst the engine is operating on viscous fuel for long periods at greatly reduced speeds is always found on the exhaust valve side of the fuel nozzle. The cause of this is that when the engine, and consequently the fuel pumps, are operating slowly, the re-seating of the fuel needle valve is not so prompt and positive as when the engine is

operating at full speed, with the result that a very thin film of fuel remains on the outer surface of the nozzle after the valve closes. Moreover, when the speed of the engine is reduced the flow of fuel between the heater at the fuel pump suction and the fuel valves is also reduced, consequently the temperature of the fuel when it reaches the fuel valves is lower than when the engine is operating at normal full speed, and this also will make for less prompt and positive closing of the needle valve.

This film of fuel on the fuel valve nozzles may be little more than a dampness, but it would seem that it remains in position during the working and exhaust strokes of the piston and until the air inlet valve opens, whereupon the warm supercharge air sweeping across the cylinder in the direction of the exhaust valve causes the film of oil to spread in that direction. The film of fuel having been thinned in the process will be more susceptible to heat and consequently will be carbonized during the subsequent working stroke. Furthermore, when an engine is running at reduced speed the time that the air inlet and exhaust valves are open together is proportionately greater, which is conducive to the thinning of the oil film and its ultimate carbonization. Fig. 6 shows the deposit tapering away towards the exhaust valves.

In the main the injection pressure with hydraulically operated valves depends upon the spring load on the needle valve and the degree of atomization upon the diameter of the spray holes in the nozzle. The lift of the needle valve does not normally affect the injection pressure, degree of penetration nor degree of atomization. The amount the needle valve is permitted to travel, however, is important. Should the travel be insufficient to allow the fuel charge unrestricted passage the load on the fuel pump will be unduly increased, while if the travel is more than necessary the prompt closing and instantaneous cut-off of the fuel supply to the cylinder, so very necessary to prevent formation of deposit on fuel valve nozzles, may be adversely affected.

Most engine builders stress the importance of a definite amount of needle valve lift, the amount being about 1 mm. on engines of a size installed in the *Auricula*. Numerous tests were made during these experiments to ascertain the effect of varying the amount of lift and it was found that the best results were obtained when the maximum area of opening was 50 percent greater than the total area of the spray holes. The greater the lift, the more forcibly will the needle valve re-seat, and when Diesel fuel is in use signs of hammering occur if the lift is too great. With high viscosity fuel, however, there is an understandable cushioning effect and the parts do not wear to the same extent but, as mentioned earlier, the action of the needle valve is not so prompt. The original needle valve lift on the *Auricula* and other ships propelled by Burmeister and Wain and M.A.N. engines was 1 mm., and this was increased to 1½ mm. in all cases.

To insure the proper combustion of the fuel charge the whole of it must ignite and burn whilst suspended in air. This can only result if every particle is driven into the cylinder with the requisite force. It is at the beginning and the end of the injection process that this is least likely to occur and conditions produced conducive to the formation of deposit on the fuel valve nozzles.

As regards the beginning of injection, insufficient injection pressure is most likely to result from a worn fuel cam peak or to the needle valve being shrouded as a result of hammering or repeated grinding. The former fault will increase the period during which the pressure required to lift the needle valve is built-up and the first of the fuel charge may not, in consequence, be driven into the cylinder with suffi-

cient force, while in the case of the second fault the needle valve will require to be lifted clear of the shrouding before injection proper begins. Before this occurs a portion of the fuel charge will have escaped past the parallel part of the needle valve and due to wire-drawing will enter the cylinder at a pressure well below the normal injection pressure. A photograph of a faulty fuel valve nozzle after it had been cut to disclose the fault is reproduced in Fig. 14.

The closing action of the needle valve, which must also be prompt and positive, is not likely to be affected by normal wear of the fuel cam peak, but a shrouded needle valve would have a serious effect and result in the formation of droplets on the nozzle, which would be quickly carbonized. The fault may not be serious enough to cause trouble when operating on Diesel fuel but it will become more apparent on boiler fuel, and the fuel rather than the valve may be held responsible. To function properly these valves must be a free sliding fit in their guides without measurable clearance, and the employment of more viscous fuel may result in the closing action being slightly less positive.

In order that the whole of the fuel charge will be injected at a pressure which will insure every particle of it burning completely in the allotted time the width of the needle valve seat is also important, the narrower the point of contact between the needle valve when in closed position and the nozzle, the more likely will prompt opening and closing result. This is important when burning low viscosity Diesel fuel but it is much more important when burning high viscosity boiler fuels. With the latter grade there will be a greater degree of wire-drawing at the instant the needle valve breaks and makes contact with the nozzle at the beginning and end of the injection period and, consequently, the greater will be the drop in pressure driving the fuel into the cylinder at these points of the process.

FIG. 14—Fuel valve nozzle after being cut to disclose fault

At the present time it is the practice for ships' engineers to grind-in needle valves when they begin to leak, and although the abrasive material used is usually far from satisfactory, the desired result as regards fluid-tightness is obtained. The effect, however, is to increase the width of the seat and remove one cause of improper combustion by introducing another of the same order, since the effect of each is to cause a portion of the fuel to enter the cylinder at a pressure very much less than that necessary to insure proper atomization, penetration and, consequently, combustion.

The wear-resisting properties of the materials used in the manufacture of fuel valve needles and nozzles have improved so much in recent years that it is now usual for such parts to operate for well over 2000 hours without showing any increase in the width of seat. It would seem that the time has now come when the practice of grinding-in

such valves on board should be discouraged and the needles and nozzles sent back to the makers for reconditioning at regular intervals. As the desirable narrow seat is obtained by making the angle of seat slightly different from the angle of the needle valve, the damaging effect of grinding-in, even with the finest abrasive paste procurable, is understandable.

To insure proper injection of fuel the conical end of the needle valve should make contact with the seat in the nozzle, as shown enlarged in Fig. 15. As time goes on the contact surface tends to spread downwards and when it reaches the condition shown in Figs. 14 and 16, prompt and positive start and finish of the injection process will not result. It will be appreciated that so far as the cut-off of the fuel is concerned the wider the seat the greater will be the quantity of fuel between the conical surfaces, which must be displaced by the re-seating needle before actual cut-off takes place.

To illustrate how deposit can be formed on the fuel valve nozzles an actual case will be quoted. The 8-cylinder 4000 i.h.p. engine of the *Dromus* was equipped to burn fuels of a viscosity of round about 1500 secs. Red. I at 100 deg. F., and so long as bunkers of that grade were lifted all went well. The ship then took on bunkers of 400 secs. viscosity and in the space of two months the eight main engine fuel valves had to be taken out six times in order to remove the heavy accumulation of deposit from the outside of the nozzles. The deposit built up until it reached such proportions that the sprays were affected and the engine exhaust became badly discolored. When this occurred the engine had to be stopped, valves removed, nozzles cleaned without dismantling and valves refitted, after which the engines would again operate satisfactorily for a time.

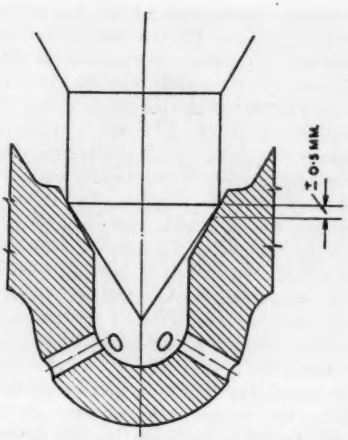



FIG. 15—*Fuel valve needle and nozzle showing where contact should be made when in closed position*

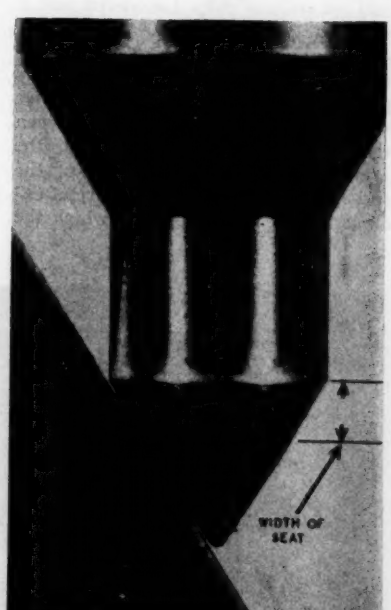



FIG. 16—Conical end of fuel valve needle showing how wear takes place

Before being re-fitted the fuel valves were tried out by the test pump and appeared to spray satisfactorily at 2500 lb. per sq. in., which was the designed spring load. The designed lift of the needle valves was 0.75 mm. In an endeavor to overcome the trouble the chief engineer increased the needle valve lift of three valves to 1½ mm., and although he reported a slight improvement it is questionable if this alteration had such an effect. The chief engineer also varied the temperature of injection between 180 and 140 deg. F. and the temperature at which the fuel was purified, but without the desired result. To eliminate the possibility that enlarged spray holes were the cause, new nozzles of the same design were fitted, but the accumulation of deposit continued.

The effect which a lower viscosity would have upon the degree of atomization, penetration and formation of the fuel sprays was fully considered and it was finally decided that as the injection pressure in these automatically operated fuel valves is dependent mainly upon the strength of the needle valve spring, which was the same as when the more viscous fuel was used, the probability was that the angle of the fuel sprays had increased. A careful examination of the manner in which the deposit built up supported this view, since it appeared as though deposit began on the end of the fuel valve housing and closed in on the nozzle as it accumulated. When the trouble began the construction of the lower end of the fuel valves, and the amount of deposit which accumulated in 144 hours full power operation, are illustrated in Fig. 17.

The first step in an endeavor to overcome the trouble was to machine the cap nuts of seven fuel valves, as shown in Fig. 18, and one as shown in Fig. 19. After a short full power run of 84 hours the fuel valves were removed for examination and the amount of deposit shown in Fig. 18, is typical of that found on the nozzles of all valves altered as shown in the illustration. The nozzle of the valve whose cap has been altered as shown in Fig. 19, was entirely free of deposit. The result of this test proved that the angle of spray had increased so much that a portion of the fuel charge became de-atomized upon making contact with a metal part in the vicinity of the fuel valve nozzle and carbonized during the subsequent combustion processes.

The number of ships that have been operated on boiler fuels up to 1500 secs. viscosity is so great and the period of

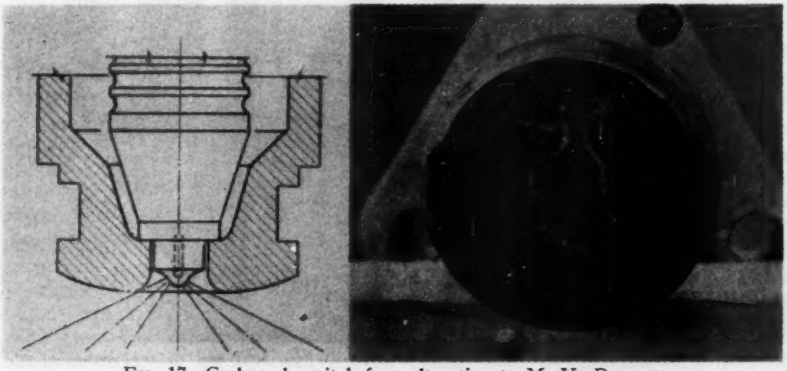


FIG. 17—Carbon deposit before alteration to M. V. *Dromus*

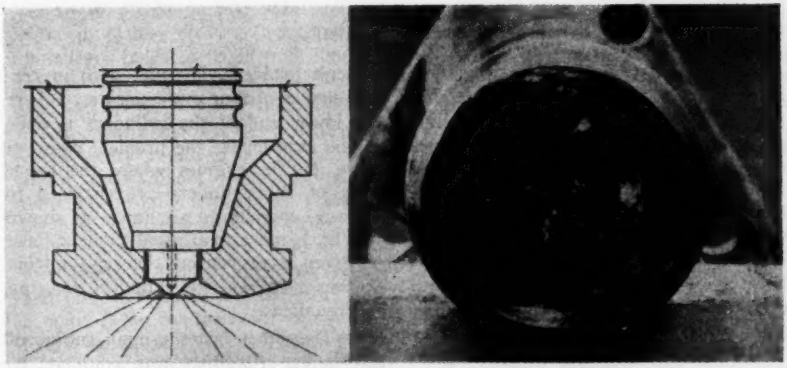


FIG. 18—Carbon deposit after first alteration to M. V. *Dromus*

service so long that it can categorically be stated that fuel within this range shipped in any part of the world can be successfully burnt in four-cycle type engines of the makes referred to earlier in this paper providing it is first treated in the manner recommended, and the various parts of the engine concerned with the injection and combustion of the fuel are in good order.

Boiler fuels are usually quite stable under treatment but it may happen that a fuel which deposits an unusually large quantity of sludge in the purifier bowl is shipped and more frequent cleaning of the bowl becomes necessary. The operation of the engine is, however, in no way affected by such fuels, which are generally made up of fuels of different types and origin. Of sixteen ships that have shipped bunkers of various grades in all parts of the world during the past three years only on one occasion was it necessary to clean the purifier with more than usual frequency.

The successful burning of boiler fuels of the grades referred to depends, therefore, upon the ability of the engines to burn such fuels. If difficulties are experienced the fault will generally be found in the engine rather than in the fuel which, after all, is bought as an under-boiler grade and not primarily as a Diesel fuel.

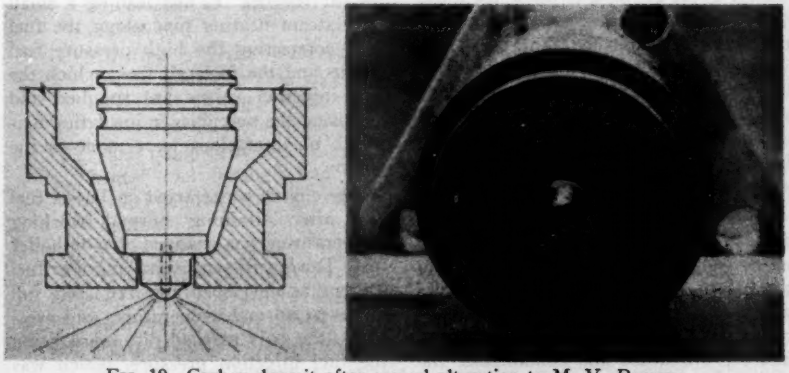


FIG. 19—Carbon deposit after second alteration to M. V. *Dromus*

## TWO-CYCLE ENGINES

So far four-cycle single-acting type engines only have been referred to, but in view of the high proportion of ships propelled by two-cycle type engines many must be concerned with the ability of this type of engine to operate satisfactorily on boiler fuels. As regards the combustion chamber end of the cylinder there should be no difficulty in burning such fuels in two-cycle engines, providing the fuel is first purified in the manner recommended and that all parts of the fuel injection system are in good order. The effect of faulty parts will be the same in both types when burning boiler fuels.

It has already been mentioned that when burning boiler fuels the cylinder liners tend to wear parallel, the wear rate at the combustion chamber end being the same as when burning Diesel fuels but the wear rate of the lower end of the cylinders becomes greater. This, it will be remembered, was attributed to corrosion wear resulting from the burning of fuels having a high sulphur content, and the products resulting from this corrosion wear naturally find their way to the open, lower ends of the cylinders. In most two-cycle engines a deep piston is employed, and in order to avoid the height of the engine being unduly great the makers cause the lower end of the piston to reciprocate through the upper end of the crankcase. Provision is usually made to retain the lubricating oil in the cylinder by fitting scraper rings at the lower end of the cylinder and oil is prevented from leaving the crankcase by scraper rings situated at the upper end of the crankcase.

With this form of construction it is reasonable, therefore, to assume that unless special consideration is given to the means provided to collect any deposit thrown out of the bottom of the cylinders, such deposit will find its way into the crankcase and contaminate the lubricating oil therein. Similar, but less difficult problems are met with in certain makes of four-cycle engines. Where the lower end of the cylinders is open to the atmosphere the problem does not arise, but in engines where the lower ends of the cylinders are enclosed to form a supercharge air pump, as shown in Fig. 1, more than usual thought must be given to preventing the deposit from the lower ends of the cylinders entering the crankcase.

In December last the main engine of the tanker *Paludina* was equipped to burn fuels having a viscosity up to 1500 secs. Red. I at 100 deg. F. The ship, which was put into commission in January 1949, is propelled by a 3-cylinder Doxford opposed piston engine, the size of cylinders being 600 × 2320 mm. (combined stroke) developing 2500 i.h.p. at 112 r.p.m. Prior to December 1949 the engine, which is of standard design in every respect, had operated with complete satisfaction on normal grades of Diesel fuel of a viscosity ranging between 40 and 100 secs.

Before installation in the ship the engine was subjected to shop trials. After initial tests on Diesel fuel the engine was run on purified 1500 secs. fuel, transported by rail car from St. Peter's Works. Apart from injecting the boiler fuel at 180 deg. F. and leading a small bore steam heating pipe along the fuel pipe connecting the high pressure fuel pumps and the fuel rail from which the fuel injection valves are supplied and enclosing the two pipes in insulating material, no alterations were made to the engine.

The engine was started on Diesel fuel and after attaining normal working temperatures was changed over to boiler fuel. During fifteen hours on boiler fuel the engine developed approximately full power at normal temperatures and pressures, the only marked difference being the fuel injection pressure, which was 7000 lb. per sq. in. as against 6000 lb.

per sq. in. on Diesel fuel. The fuel nozzles, or plates, on this occasion contained six holes of 0.025 inch diameter the standard nozzle for Diesel fuel having five holes of 0.022 inch diameter.

After this short test the fuel injection valves were removed for examination and a small amount of carbon found on the extreme inner ends of all valves. In the case of two valves the carbon was hard and two holes in the spray plates were choked. At one spray hole the carbon had built up to a distance of about 5 mm. The condition of other parts likely to be adversely affected by the burning of boiler fuel was no different than would have been the case had the engine operated on Diesel fuel. This shop test could not be extended without delaying the work of installation on board, but though of short duration it provided much useful information regarding the burning of boiler fuels in this particular type of engine and enabled decisions to be made as to the alterations required to insure satisfactory operation under service conditions.

During the time the ship operated at sea on Diesel fuel certain additional parts were prepared and when ready the ship was directed to a port where the alterations could be carried out. The alterations and additions comprised the following:—

(1) The provision of fuel purifying equipment as installed in the *Auricula*.

(2) All fuel injection valves modified to enable heated fuel to be circulated through them whilst the engine is inoperative.

(3) Hand pump provided to circulate heated fuel through fuel pumps and injection valves prior to starting.

(4) A drainage system to lead fuel ejected from fuel injection valves to a receptacle situated under the high-pressure fuel pumps.

(5) Drain valves provided in high-pressure fuel pumps to enable cold fuel to be drained off.

(6) Unlagged steam heater installed directly under high-pressure fuel pumps to maintain temperature of fuel during inoperative periods.

(7) The six-hole fuel nozzles or plates replaced by plates having five holes of the same size, i.e., 0.025 inch.

(8) Steam heating pipes of ⅜ inch bore clipped close to fuel pipes connecting high-pressure fuel pumps to distribution box, distribution box to filters and the filters back to fuel valves. The steam heating and fuel pipes were encased in insulating material.

(9) Pipes conveying fuel from heater to high-pressure fuel pump suction insulated to prevent loss of heat.

Upon completion of this work the ship was taken to sea and the engine operated at various speeds. Maneuvering trials on 1100 secs. fuel were also carried out and whilst time did not permit complete data to be recorded of what was happening inside the cylinders, the engine operated satisfactorily to all outward appearances. The fuel was burnt with a clear exhaust and the fuel injection valves at the end of the trial were free of deposit and all spray holes clear. The fuel injection pressure was 6500 lb. per sq. in. and the temperature at the moment of injection 175 deg. F. After the trials the ship proceeded to Aruba without further delay, with instructions to operate on Diesel fuel until clear of the English Channel.

The voyage to Aruba was completed without incident, apart from very minor troubles, and at normal speed. When exceptionally heavy weather was encountered the chief engineer, in collaboration with the Doxford representative on board, decided to operate the engine on Diesel fuel.

Before the engine began operating on

boiler fuel a complete record was obtained of the condition of the engine, such as wear of cylinder liners, composition and physical properties of crankcase lubricating oil, amount and composition of matter in scavenging air and exhaust passages, etc., so that when the engine has operated for an equal time on the cheaper fuel an accurate comparison can be made. The piston rings throughout the engine were removed prior to being operated on boiler fuel.

On arrival at Aruba No. 2 cylinder was opened up for examination and all parts found in good order, with the exception of the piston rings, all of which had worn excessively in a radial direction and were consequently renewed. Before leaving Aruba sufficient bunkers of 1420 secs. viscosity were taken on board to return the ship to the U.K. The homeward voyage was made without incident and the weather was sufficiently favorable to enable the following operational data to be collected:—

| | *Diesel fuel* | *Boiler fuel* |
|---|---|---|
| Fuel in use, secs | 37 | 1420 |
| Injection pressure, lb. per sq. in. | 6200 | 6500 |
| Scavenging pressure, lb. per sq. in. | 1.95 | 1.8 |
| Exhaust temperature, deg. F. | 593 | 610 |
| Compression pressure, lb. per sq. in. | 334 | 325 |
| Maximum pressure, lb. per sq. in. | 575 | 568 |
| Mean effective pressure, lb. per sq. in. | 84 | 88 |
| Total i.h.p. | 2758 | 2881 |
| R.p.m. | 108.5 | 108 |
| Daily fuel consumption, tons | 10.08 | 9.5 |

The data when operating on Diesel fuel was obtained during the official sea trials of the ship, and in comparing the results obtained on that occasion with the results obtained subsequently when operating on boiler fuel, the following is discussed:—

(1) The fuel injection pressure is the greater by 300 lb. per sq. in. owing to the higher viscosity of the boiler fuel.

(2) The exhaust temperature is 17 deg. F. higher due partly to the lower scavenging air pressure.

(3) The compression pressure is 9 lb. per sq. in. lower. This is accounted for by the fact that when on Diesel fuel all piston rings were in new condition, whereas soon after the figure when on boiler fuel was obtained the piston rings had to be renewed.

(4) The maximum pressure is slightly lower due to the slower burning rate of boiler fuel, but the amount is not as great as in other engines referred to in this paper because in the Doxford engine the fuel injection process begins much earlier.

(5) The mean indicated pressure, and consequently the horsepower, is greater when operating on boiler fuel. The reason for this difference is rather difficult to explain as the slightly greater fuel injection pressure would not account for the difference. The explanation may be that one of the two pressure indicators used was not registering correctly.

(6) The high fuel consumption when burning Diesel fuel is accounted for by the engine not having

been run-in to the same extent as when the data for boiler fuel operation was obtained.

As mentioned earlier, the *Paludina* operated on Diesel fuel during the first nine months after commissioning and the average daily fuel consumption for an output of 2870 i.h.p. was 9 tons, or one-half ton less than when operating on boiler fuel. When the correction for difference in calorific value (Diesel 19,300, boiler 18,500 B.Th.U.) and horsepower developed was made, the daily consumption is found to be 0.1 ton greater when operating on boiler fuel.

Under (2) it is mentioned that the exhaust temperature is 17 deg. F. higher when burning boiler fuel and that this is partly due to the lower scavenging air pressure. No attempt has been made to represent the additional heat in the exhaust gases in terms of fuel weight when burning boiler fuel, but if due allowance is made for the lower scavenging air pressure it will be seen that when this engine is burning boiler fuel the combustion efficiency is very little different, if there is any difference, to what it is when burning Diesel fuel.

When the *Paludina* reached a home port the following had been accomplished while burning boiler fuels having a viscosity between 900 secs. and 1500 secs.:—

| | |
|---|---|
| Hours operating at full power. | 894, of which 626 on high viscosity fuel |
| Number of ports entered..... | 4 |
| Total revolutions made..... | 5,881,800 |
| Quantity of fuel consumed.... | 248 tons high viscosity fuel and 89.5 tons Diesel fuel |
| Sludge removed from purifier. | 3 oz. per ton |
| Sludge removed from clarifier. | 1½ oz. per ton |

Nos. 1 and 3 piston rings were renewed because they were found to have worn excessively in a radial direction. On the bottom of the scavenge air trunk greasy matter to a depth of ¼ inch or so was found, but the crankcase was clean and the lubricating oil therein was, judging by appearance, in good condition. In every other respect the engine was in normal condition and when it has operated for a length of time sufficient to enable full information to be obtained regarding cylinder liner wear, effect upon crankcase lubricating oil, etc., it is felt that the results will be encouraging.

The high wear rate of the piston rings, although greater than in other engines referred to, is not peculiar to this particular type of engine. When the opportunity occurs to fit rings of a better grade of material it is expected that the wear rate will be substantially reduced.

## PRE-HEATING FUELS

It has not, of course, been necessary to pre-heat any of the normal grades of Diesel fuel, either for transferring from one compartment to another or for injecting into the engine cylinders, under even the most severe climatic conditions. With high viscosity fuel, however, pre-heating is necessary, and for transferring from one compartment to another the amount of heat to be applied depends upon the viscosity of the fuel, the relative positions of the transfer pump and the compartment from which the fuel is taken, as well as the type and condition of the transfer pump. Assume here that the pump is of the reciprocating or rotary displacement type and that it is in good working order.

For fuels with a viscosity under 900

secs. Red. I at 100 deg. no pre-heating is required to transfer from one compartment to another if the situation of the tank from which the fuel is to be taken is such that there is a head of pressure at the pump suction. This applies to crossbunkers, deep tanks and gravity tanks. When such fuels require to be lifted through a distance of about six feet, as for instance when drawing from double-bottom tanks, a steam coil around the suction tail pipe is all that is required. The diameter of the coil should be about twice the diameter of the tail pipe and its location as low as practicable. For double-bottom tanks pre-heating becomes necessary when the temperature of the sea falls below 65 deg. F. At higher sea temperatures 900 secs. fuel can be lifted without pre-heating.

For handling of more viscous fuels, up to 1500 secs. Red. I at 100 deg. F., it is advisable for fore deep tanks, crossbunkers and double-bottom tanks to be fully coiled. The amount of heating surface required in fore deep and double-bottom tanks is 1 sq. ft. per ton, and in the case of crossbunkers situated adjacent to the engine-room, ½ sq. ft. per ton of tank capacity. With fuels in this range it has been found that steam heating does not become necessary for drawing from crossbunkers until the sea temperature falls below 45 deg. F.

In tankers the usual procedure is to consume the fuel in the crossbunker first, then heat the double-bottom tanks or fore deep tank and transfer the content of both these tanks to the crossbunker. In other types of ships where this fuel is stored in the double-bottom ballast tanks it is necessary to have these tanks fully coiled in order to transfer the bunkers daily to the settling tanks. Steam, of course, is only applied to the alternate tanks in use at any one time in order to suit trim of ship.

When fuel up to 3500 secs. Red. I at 100 deg. F. requires to be handled the foregoing pre-heating arrangements will be suitable, but there will, of course, require to be a longer period of pre-heating. In the case of crossbunkers heat will require to be applied only after the temperature of the sea falls below 65 deg. F., as above this temperature the fuel can be pumped at a reasonable rate. At sea temperatures below 65 deg. F. it is advisable to maintain this grade of fuel at a temperature of 90 deg. F., when it can be readily transferred at any sea temperature. When fuel of this grade is stored in the double-bottom ballast tanks of dry cargo ships a temperature of 120 deg. F. will have to be maintained in alternate tanks from which the settling tanks are supplied, as is done in steamers burning liquid fuel under boilers. In the event of the cargo being of a perishable nature such a high temperature would not be permissible, in which case the fuel should be heated to about 100 deg. F. only and a longer time allowed for transfer of bunkers. If a temperature of 100 deg. F. is not permissible a fuel of lower viscosity will have to be shipped.

The two settling or daily service tanks usually provided in motorships should be fitted with heating coils. One tank, known as the dirty oil tank or untreated fuel tank, receives the fuel from the storage tank in readiness for passing through the purifying plant, while the other tank receives the purified fuel in readiness for use in the engine. The temperature of the fuel in the dirty oil tank should only be sufficient to enable the fuel to flow freely to the heater of the purifying plant, while the temperature of the fuel in the clean oil tank should be such that the fuel will flow freely to the engine fuel heater. In each case a temperature of about 100 deg. F. suffices for the most viscous fuels referred to here, and as these daily service tanks are generally situated at the upper part of the engine

a few coils of steam heating pipe around the fuel outlet is all that is required. The fuel transfer pump discharge connections should be so arranged that it is impossible to pump up the clean oil tank from the storage tanks and thereby contaminate the purified fuel.

## CONCLUSION

Several matters which may be considered outside the province of the marine engineer, but which are of particular concern to him, have been touched upon in this paper in the hope that those who have specialized knowledge of such matters as metallurgy, petroleum technology, lubricating oils and, particularly, piston ring manufacture, will come forward and pass on the benefit of their experience, as it is only by close cooperation between the various branches of the industry which produces ships' machinery that progress can be made.

In preparing this paper an earnest endeavor has been made to give a full and frank account of the work done and the results obtained. Certain information might have been given in greater detail, but where this is found to be the case the reason is not that there is a desire to conceal anything, but simply that consideration had to be given to the length of the paper.

# THE RADIO BACKGROUND OF RADAR

ACKNOWLEDGMENT

The *Journal of the Franklin Institute* for October, 1950 carried Prof. HENRY GUERLAC's article on the historical background of radio detection equipment. Prof. GUERLAC is Professor of the History of Science at Cornell University.

Radio detection devices using the pulse-echo principle were developed independently and almost simultaneously during the 1930's by a number of the great powers. In 1939 closely guarded secret programs were in various stages of advancement in Great Britain, France, Germany, Canada and the United States. Russia, China, Japan and Italy were at that time without the equipment and seem to have acquired it after the outbreak of war, by capture and by disclosures from their allies. In France and Germany, radar was developed in commercial laboratories under military supervision, whereas in Great Britain and the United States the pioneer work was done by the armed services.

Such a duplication of effort will surprise only those who cling to a Hero Theory of scientific progress and demand for each discovery a single putative inventor; or those who are unaware of the frequency—one is tempted to write, the regularity—with which such parallelisms are encountered in scientific work. The duplications are by no means rare in pure science; but they are much more common in applied research, where a significant discovery, simultaneously taken up by many hands, can spawn a numerous progeny of practical applications and useful embodiments. The chances of duplication are better in the present century than in the last, for in the final analysis they depend only upon the scope and intensity of the research effort. It has been well said that the greatest invention of the nineteenth century was the art of inventing; and this is an art which the twentieth century has greatly extended and perfected by widespread technical education, well-financed team research, generous budgets, and well-equipped laboratories. The element of chance in scientific progress (which includes also the chance of discoveries by isolated individuals being lost to society) is steadily diminishing, and the discontinuities in the upward curve of technical progress, though they are still present, are less pronounced.

Each striking instance of parallel and independent discovery raises a number of fundamental historical questions. When, moreover, a real burgeoning takes place we are led to ask what the conditions were that favored it. The main influences are obvious. First of all, when a serious effort is put behind a development, as in the case of radar, it is evident that this development satisfied a clear and urgent need. Second, since the principle of *nihil ex nihilo* ap-

plies quite as surely to the history of science as to science itself, it is obvious that some key principles or central ideas in pure science must have been the point of departure. Lastly, if success is finally attained, it is certain that the state of the art, that is to say the perfection of engineering skills in this and neighboring fields, must have reached a point where success was fairly well assured.

It is proposed in this paper first to analyze the military need for radio detection equipment, and then to explore the background of scientific ideas and technical progress that together made possible or perhaps inevitable the development of radar before World War II. Conditions were definitely propitious in the period 1930-1939; so much so, in fact, that, although there were important adumbrations long before, it is hard to imagine a successful development much before that time.

## THE REPLY TO AIR POWER

Radar was at first envisaged solely as a defensive weapon against hostile aircraft. The first types to be designed were long-range, high-power sets to give early warning against attacks by enemy planes, or sets with shorter range to provide accurate information for the direction of searchlights or the pointing of anti-aircraft guns. Viewed in historical perspective, radar will probably appear as the reply, the countermeasure, to the threat of air power.

Perhaps we are still too close in time to realize fully that the ten years before World War II were the years that introduced the age of air power. In 1930 we were still marveling at Lindbergh's solo flight to Le Bourget. By 1940 a series of technological changes had made routine commercial transatlantic flights a certainty.

While commercial air transportation became a commonplace during that decade, cruising speeds rose steadily. In 1931, Post and Gattie flew around the world in eight days; while in July, 1939, Howard Hughes cut this time in half, and maintained an average flying speed of 206 mph. On the eve of World War II, the principle countries of the world could all point to two- or four-motored aircraft in routine service having cruising speeds in excess of 200 mph. There was no doubt that existing aircraft warning devices were hopelessly archaic and inadequate, and serious efforts were being directed towards finding a completely novel type of device.

## AIRCRAFT DETECTION IN THE FIRST WORLD WAR

Even the circumscribed role of aircraft in the First World War gave rise to methods of detection. This was limited in practice to detecting the sound of an approaching plane and determining its direction; but methods were also proposed for detecting and amplifying electromagnetic radiation (on radio and infra-red frequencies) emanating from the plane.

Sound detection seems to have begun, on the Allied side at least, with the "orthophone," a simple binaural device used in the French Army in 1917. At roughly the same time an acoustical detector of the reflector type was produced in England by the Anti-Aircraft Section (under Dr. A. V. Hill) of the Munitions Invention Department (1).*

By 1936 acoustical detectors had

* The numbers in parentheses refer to the references appended to this paper.

reached a point where an error of only ¼° in azimuth was obtained on sounds from a fixed source. For an airplane flying at moderate heights all sound locator manufacturers quoted a 2° accuracy. In certain cases the sound was even converted into visual information on the screen of a cathode-ray oscilloscope.

These devices gave no range information; their performance depended upon the wind, and they were quite unreliable on gusty days. The velocity of sound is so low, and the range was so short, that with the high speed of modern planes observers scarcely had time to alert the defenders; certainly there was not enough warning to send up intercepting fighters. The main function of this equipment was to direct searchlights.

While with the AEF in France in the First World War, Edwin H. Armstrong, then a Major in the Signal Corps, conceived the idea that perhaps the extremely short radio waves produced by the spark gaps of a gasoline aircraft engine could be used to detect enemy aircraft. To solve the difficulty of detecting and amplifying such short waves, Major Armstrong developed the first superheterodyne receiver, but it was never used in World War I for the purpose for which it was devised (2).

Almost simultaneously a second method of attack—the attempt to detect the infra-red radiation from airplane engines and exhaust gases—was adopted early in 1918. Master Signal Electrician Samuel O. Hoffman and a group of enlisted men working under Professor George Pegram at Columbia University attempted to detect objects at higher temperature than their background by means of a thermophile mounted in the focus of a parabolic mirror (3). With this equipment in the spring of 1918 men were detected at 600 ft. In August 1918 an apparatus of this kind was sent overseas, but tests in France proved unsuccessful. Meanwhile thermal equipment specially modified to detect aircraft was tested at Langley Field, Va., where ranges from 4000 ft. to over a mile were reported but with complications from false indications caused by clouds.

No further work on heat detection was carried on by the Army until 1926 when the Ordnance Department set up at the Frankford Arsenal a project for the "Investigation of Detection Devices using the Infra-Red Ray," under the direction of Captain William Sackville, C.A.C. This was a continuation of graduate research conducted with Lieutenant José R. Olivares, Philippine Scouts, U. S. Army, at M.I.T. (4).

The problem had been suggested by Professors Vannevar Bush and J. W. Barker, and under their direction the principal avenues of approach to the detection problem were reviewed—all, that is, except the use of *reflected* electromagnetic waves from a ground source. They rejected sound because of the time lag, short wave radio waves from the engine ignition system because of the ease of shielding, and for similar reasons visual observation of the exhaust flare, and focused their attention on the infra-red energy from the engine exhaust. But experiments at M.I.T. and at the Frankford Arsenal were not much more successful than the closely similar Hoffman experiments.

## DETECTION WITH REFLECTED ENERGY

The radar principle is divisible for purposes of analysis into two elements: detection by means of reflected radio energy (the echo principle) and the determination of range by means of carefully timed pulses (the pulse principle).

The earliest echo detection device was of course the human voice; a

stentorian halloo from the bridge of a ship has often given the skipper of a fog-bound ship some notion of his proximity to land. But in the last century John Tyndall, the British physicist, at the request of the Elder Brethren of Trinity House, experimented with lights and with crude electrical contrivances and finally suggested the use of steam whistles to prevent ships from running ashore at night (5).

In 1912, after the sinking of the *Titanic,* Sir Hiram S. Maxim proposed to detect icebergs and other obstacles by sending out low-frequency sound waves, below the audible, and receiving the returning echo on a diaphragm (6). Maxim compared his method with Abbé Spallanzani's experimentally blinded bats (1794) which Maxim believed avoided obstacles by detecting the echo of low frequency sounds produced by their own wings (7).

## THE REFLECTION OF RADIO WAVES

It is possible to detect invisible or distant objects by means of radio and infra-red energy only because such radiation has, like light, the property common to the whole spectrum of being reflected from obstacles. It is only because such waves can be focused into directed beams of radiation that efficient utilization of energy is possible, and that detecting devices can act as direction finders or locators.

In the case of radio, this property is only readily observable for wave lengths a few meters in length or shorter. That is why attention was not drawn to reflection phenomena while interest was centered on broadcast frequencies, although these effects were prominent in the earliest experiments on radio waves.

In his great *Treatise on Electricity and Magnetism* (1873), James Clerk Maxwell brought under unified theoretical dominion the known facts concerning light, electricity and magnetism. The most striking consequence of Maxwell's electromagnetic theory of light was the prediction that there were other as yet undiscovered waves propagated through space with a velocity equal to that of light; that these are produced wherever oscillatory electric currents are set up, as for example in a discharging Leyden jar; and that they should be reflected from conducting surfaces and refracted by dielectrics according to the classical laws of geometrical optics. The existence of these radio waves was first experimentally verified in 1887-8, nearly ten years after Maxwell's death, by Heinrich Hertz. Hertz's experiments, once he had succeeded in generating and detecting the earliest known radio waves, were designed to prove that these waves did in truth have the resemblance to light, or as we say today, the quasi-optical properties, which Maxwell had predicted.

Hertz used wavelengths which made the optical properties easy to observe (8). In his first experiments his spark gap gave him waves 10 meters in length; subsequently with a much smaller oscillator he obtained a wavelength only 66 cm. His transmitter was placed in the focal line of a cylindrical metal reflector; his receiver consisted of a dipole in the focal line of a receiving reflector; the dipole was connected with a spark gap. With this equipment Hertz was able to detect radiation when the cylinders were separated by several meters; and with it he was able to duplicate many of the phenomena encountered in the study of light. He showed that shadows were cast when objects opaque to the radiation were interposed; he observed the phenomenon of diffraction; and he showed by rotating the receiving cylinder through 90° that the waves emitted by his oscillator were polarized.

This was further confirmed by beautiful experiments in which he employed a grating of wires interposed between the transmitter and receiver; when the wires of the grating were at right angles to the linear radiator and to the receiving dipole the energy passed through; but when the screen was rotated through 90° the screen was opaque to the radiation. It likewise proved possible to refract electromagnetic waves. With a large prism of pitch cast in a wooden box Hertz was able to observe a refraction of as much as 22°; and from this result he was able to calculate the index of refraction of pitch for his waves to be 1.69, as compared with a value of 1.5 and 1.6 for similar substances when transmitting light.

In the decade following the publication of Hertz's results a number of different workers—Righi, Klemencic, A. D. Cole, Lebedew and others—extended Hertz's work by using what we now call microwaves (9). With extremely short waves a few centimeters in length, generated at very low power, they were able to perform quasi-optical experiments which had not been possible with Hertz's somewhat longer waves (10). For example, Peter Lebedew in Moscow succeeded in demonstrating, by means of 6-mm. waves, that radio waves could be doubly refracted by crystals (11).

While the attention of physicists was quite generally focused on the microwaves and their optical properties, interest was soon drawn to the possibility of wireless telegraphy by means of the new Hertzian waves. In his first successful transmissions on Salisbury Plain in 1896, Marconi used parabolic reflectors behind both his transmitter and receiver, and established communication at a distance of one and three-quarters miles using waves a meter in length.

Almost at once, however, he turned to much longer waves, principally because it was much easier to get high transmitter power at these wavelengths; also because they proved much better adapted to long range communication than shorter waves which are strongly attenuated over land or water. Still later, in 1901, Marconi's extraordinary success in bridging the Atlantic with radio waves revealed that certain of the lower frequencies, at least, were not limited in range by the earth's curvature.

## THE RETURN TO SHORTER WAVES

During the First World War there was a sudden revival of interest in directed transmission, and hence in shorter wavelengths, because of the military possibilities of secret point-to-point beam communication. These possibilities were explored in 1917 by the French and by the Signal Corps Research Laboratory of the AEF in Paris; and a few years later by the United States Navy. The only work published in detail was that of Marconi and C. S. Franklin in 1916-17 (12). These men worked in England and in Italy, in collaboration with the Italian government, and got successful transmission up to 20 miles using waves of 2-5 meters. At the end of the war interest again shifted to longer waves, although the Marconi company continued to explore the possibilities of directed radiation.

Early experiments all served to confirm the opinion that short waves—in practice any wavelength much below 200 meters—were worthless for long-range communication (13). In consequence, the amateurs were relegated to the supposedly unprofitable region of 200 meters and below. Credit for discovering the remarkable properties of this region belongs to the amateurs who

made up the membership of the American Relay League (14), the French *Société des amis de la T.S.F.* (15), and other associations.

In November, 1923, the tight little world of radio enthusiasts was startled to hear that a French amateur from Nice, Léon Deloy, had established a two-way connection across the Atlantic with two American amateurs, F. H. Schnell and J. L. Reinartz (16). This extraordinary achievement advertised the peculiar advantages of "short waves" for long distance communication. In that year and the next, forcing their equipment to the limit, and operating vacuum tubes often at ten times their rating, the amateurs of America, Europe, Asia and Australia linked up the world by radio.

Industry followed closely on their heels. The Radio Corporation of America and the Telefunken Company's station at Nauen soon established commercial short-wave transoceanic links; in 1923 the Westinghouse station KDKA began broadcasting on 100 meters to Europe and America; in July, 1924, the Marconi company signed a contract with the British government and the Dominions to build four short-wave stations to connect the metropolis with India and the Dominions.

The amateur successes were also responsible for a redoubled activity on the part of the U. S. Navy whose radio engineers had just moved into the recently-completed Naval Research Laboratory at Bellevue, D. C. Under the leadership of A. Hoyt Taylor, Superintendent of the Radio Division at NRL, a program was launched, in close cooperation with the American Radio Relay League, to explore the behavior of short waves in long-distance communication (17).

The immediate effect of this research was to raise the question of why these short waves gave such unexpectedly long range. This work, which served to open up the field of ionospheric research, will be mentioned below. The second consequence was to inspire everyone, especially the amateurs, with the desire to see whether the favorable properties of the short waves might not be accentuated as one went farther down the spectrum. The exploration of shorter waves, touched off in 1923, continued unabated during the next decade. By the end of 1925 it had been demonstrated that long-distance daytime communication was possible on 20 meters.

It was some time before industrial concerns took the lead away from the amateurs, who in July, 1924, were authorized to use four new bands: 78-80, 40-43, 20-22 and 4-5 meters (18). Those who tackled the lowest wavelength discovered that it did not enjoy the long-distance virtuosity of 20 meters. Moreover, the techniques of producing and receiving 5-meter waves required departures from customary methods, whereas conventional tubes served adequately for 20 meters. In 1927 the amateurs were allotted a new band at 10-10.7 meters. Soon after its allocation a few dozen amateurs tried it out, hoping it might duplicate the performance of 20-meter waves. The results were disappointing—mainly it turned out later, because of the sunspot cycle which in 1929 caused serious magnetic disturbances.

After 1930, industrial laboratories put an increasing emphasis upon the study of short and ultra-short waves. Important papers appeared from industrial laboratories on directive antennas and on propagation characteristics of ultra-high frequency waves (19).

At about this time widespread attempts were made to study transmission on waves 5 meters or shorter. In 1930 the Germans reported the results of successful communication experiments on 3 meters, obtaining a range of 180 miles with a 1.5 kw. transmitter (20)

and demonstrating that on these frequencies line-of-sight limited the range. In France, tests showed the feasibility of ultra-high-frequency telephonic communication on 5 meters between Nice and the Col de Teghine in Corsica. An English experimenter reported similar work on 2 meters. Between 1930 and 1935 the commercial concerns made careful propagation measurements on these wavelengths—with application to television of these frequencies clearly in mind—and confirmed the German findings as to the limited range. RCA made plans with the Mutual Telephone Company of Honolulu to explore the possibilities of ultra-high frequency waves for the establishment of inter-island telephonic links, and decided it could be done on 7 meters. In 1931, in the summer issues of *QST*, the organ of the American Radio Relay League, a campaign was launched to interest amateurs once again in the problem of communication on 5 meters. In 1934 Hull established an experimental 56-megacycle link between Boston and West Hartford, publishing the results in 1935 as an important pioneer study of line-of-sight propagation (21).

## TUBES AND TECHNIQUES FOR ULTRA-HIGH FREQUENCIES

Thus by the early 1930's, just as the need for radio detection equipment was becoming acute, the course of radio experimentation had reawakened an interest in ultra-high frequency radio waves. Electronic television at about this time provided an added incentive for the development of new techniques and devices.

It is hard to imagine radar without the cathode-ray oscilloscope. After an uneventful development dating from the last century, this indispensable instrument first appeared about 1930 as a compact, lightweight and, above all, reliable device. It was at once adopted in all branches of electronic research.

The cathode-ray oscilloscope was invented by Ferdinand Braun in 1897 (22). His was a very simple device with a flat-disc cathode, a wire anode fed in from the side, an annular diaphragm to limit the beam and a fluorescent screen of zinc sulfide. It contained air at low pressure, and closely resembled the tube used by J. J. Thomson in determining the value of $e/m$ for electrons. The Braun tube in its early form was used by Zenneck and his school in studying radio circuits and the transmission of radio waves. In 1905 an important improvement, not immediately effective, was made by Wehnelt when he suggested the use of a hot, lime-coated filament as the source of electrons. This ultimately made it possible to operate tubes at reasonable voltages. The use of early tubes was restricted because the equipment was large and cumbersome, because it required such high voltages, and because of the difficulty of maintaining a reliable vacuum. By about 1930, industrial research laboratories in the principal countries had produced compact hot-cathode tubes, operating on low voltages, that were sensitive, reliable and moderate in price. In the next few years the cathode-ray oscilloscope supplanted the mechanical oscillograph as a laboratory instrument, and found applications in a new and important field where even the best mechanical oscillographs were inapplicable: the study of wave-shapes in the higher radio frequencies.

The influence of television upon the development of radar was not as direct as the superficial similarity of the two types of equipment would indicate. Television and radar were parallel developments, and because of the secrecy which surrounded radar they did not often interpenetrate. The earliest experimental television was accomplished

in 1925-6, with mechanical scanning devices like the Nipkow disk or the later perforated drum, used for both pickup and viewing (23). Two important developments in its history took place in the early 1930's: (1) the abandonment of mechanical systems with the recognition that the future of television lay in using the cathode-ray tube both for pick-up and for viewing, as A. A. Campbell-Swinton had suggested as early as 1908, and (2) the decision to adopt ultra-high frequencies for television transmissions, despite propagation difficulties. Since television transmitters must radiate an extremely broad bandwidth of freqencies in order to transmit pictures of high definition, it was clearly advantageous to use ultra-high frequencies.

After 1930, television provided the chief commercial incentive for opening up the ultra-high frequency region. Tube and circuit development, propagation studies, and above all systematic and continued development of the cathode-ray oscilloscope were the chief dividends reaped by radar from television research during the first years. In the decade before the war, important work went forward in improving the fluorescent screen, studying the properties of phosphors, and improving the mechanical structure of cathode-ray tubes. To this should of course be added accumulated experience in the design of scanning and synchronizing circuits. Much of this influence was only felt on the eve of the war and during the war when television engineers, like ionospheric investigators, were recruited for radar work.

A large literature grew up describing the special techniques for using ultra-high frequency waves, especially the design of transmitting and receiving tubes. By about 1930 it became evident that the limit was being approached above which conventional tubes could not be dragooned into operating (24).

There are inherent limitations in conventional tubes that become increasingly critical as frequency is raised. Above 10 megacycles per second (Mc./sec.) the efficiency of tubes begins to show a sharp decline.

In the 1930's the chief electronic concerns were producing tubes specially designed for ultra-high frequencies. The Eitel-McCullough Co. in California brought out rugged transmitter tubes for the use of amateurs. And by 1934 RCA acorn tubes and Western Electric "doorknob" tubes were on the market (25). These were tubes of small dimensions with low transit time, short leads with low inductance and capacitance and very small inter-electrode capacity.

These improvements disposed of the major obstacles to pushing down into the region between 3 meters and 1 meter. Radio communication at these wavelengths, subject of course to certain limitations prescribed by the characteristics of the waves themselves, was thus clearly within reach. But to penetrate the realm of the microwaves or centimeter waves was to require a whole new art. The earliest radar, however, did not presuppose proficiency in microwaves, and radio detection devices between 10 meters and 1½ meters were strongly influenced by the developments just enumerated.

## OBSERVATIONS ON REFLECTION

With the shift to very long waves, the phenomenon of reflection was no longer readily observed and did not come into prominence until work was resumed on ultra-high frequencies during and just after World War I (26). Marconi spoke of it in his New York address in 1922, and A. Hoyt Taylor

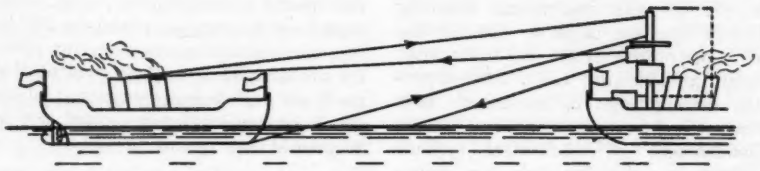


FIG. 1.

referred to it in an article published in *QST*, early in 1924 (27).

After publication in *QST* the phenomenon must have been well known to radio enthusiasts (28). Numerous references appeared in print after 1930 (29), including a report by engineers of the Bell Telephone Laboratories which has considerable historic significance as the first published account of the detection of radio energy reflected or reradiated from an aircraft. The authors spoke of the general phenomena as being "well known," but emphasized their discovery that the effect "extends to unsuspected distances at times," notably in the case of reflections from aircraft which they studied with care (30). Identical but unpublished observations had an important influence upon radio detection at the U. S. Naval Research Laboratory and in Great Britain.

It was only a step from this to the idea that such reflections could be used to detect objects in fog, darkness or limited visibility. The earliest proposal of this sort that has come to light is the patent granted in several countries to an engineer of Dusseldorf, Christian Hulsmeyer, in 1904 for a collision prevention device (see Fig. 1). This consisted of a spark-gap transmitter sending out a beam of very short radio waves focused by means of a hemicylindrical reflector located on the ship's mast. The echo is picked up by a receiving antenna also provided with a reflector. The cw. signal is detected by the coherer of a shielded receiver. The device, mounted as in a compass box to stabilize it, was rotated to determine directions (31).

No other proposal seems to have been made until after the First World War. On June 20, 1922, Marconi was guest of honor at a joint meeting in New York of the Institute of Electrical Engineers and the Institute of Radio Engineers. The occasion was the presentation to Marconi of the I.R.E. Medal of Honor in recognition of his work in wireless telegraphy. In a long address he described his communication experiments using waves a few meters in length and directional transmitters, called attention to the phenomenon of reflected radio waves, and suggested their use for detection (32):

> It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.

The earliest experimental confirmation of these speculations took place in the autumn of 1922 at the Naval Aircraft Radio Laboratory—later to become the Naval Research Laboratory—at Anacostia, D. C. The observers were A. Hoyt Taylor and Leo Clifford Young. About the middle of September, 1922, they began an informal investigation of 5-meter waves.

Their receiver was installed in an automobile and the first experiments were made on the grounds of the Naval Air Station, the transmitter being set up near the door of their laboratory, only a few feet above the ground. Almost at once interference effects were noticeable. As the car drove away from the transmitter and passed certain steel buildings from which some of the radiation was reflected a very sharp series of maxima and minima were observed. The sound was now intensified and now weakened as the car moved away from the transmitter, clearly resulting from the simultaneous reception of energy coming directly from the transmitter and reflected from the buildings.

Such things as a passing automobile, a screen door, or a network of wires, like the backstop of a tennis court, caused marked shielding effects. Experiments on the transmission of the energy over water were tried by driving the car with the receiver to Haines' Point across the Potomac. The same interference effects were also noticed, and it was discovered that they came from clumps of willow trees near the receiver. While these experiments were in progress and unobstructed signals were being received from the other side, the steamer *Dorchester,* a wooden vessel of no great size, passed down the channel. Fifty feet before the bow of the steamer crossed the line of vision between transmitter and receiver, the signals jumped to nearly twice the previous intensity. When the steamer actually passed across this line they dropped to half the normal value. Again when the stern of the vessel had passed fifty feet farther downstream, the signals rose to normal intensity, then to about twice normal, and then dropped back again.

September 27, a memorandum drawn up by Taylor was transmitted by the Commanding Officer of the Station to the Bureau of Engineering, describing the experiments and urging the possibility of directive communication on this wavelength. It also referred to the possibility of using highly directive beams for landing aircraft at night or through overcast. The report (33) urged also that "possibly an arrangement could be worked out whereby destroyers located on a line a number of miles apart could be immediately aware of the passage of an enemy vessel between any two destroyers of the line, irrespective of fog, darkness or smoke screen." The memorandum requested Bureau approval for continuance of the 5-meter work, but no encouragement was forthcoming and it was dropped. This can be considered the earliest proposal for the use of radio detection as a military device.

It was not until 1930 that the subject of radio detection raised its head once more, this time in print. In the July issue of the *Proceedings* of the Institute of Radio Engineers an English contributor wrote (34):

> It has already been suggested that icebergs, etc., might be detected by short-wave radio and it is possible, for instance, that this would be done by projecting a short-wave beam and observing whether any energy were reflected back to the source. A similar method might be employed for estimating the height of aircraft above ground.

## PULSE RANGING AND THE PULSE-ECHO PRINCIPLE

The earliest efforts to measure distance by the careful timing of pulses of energy were associated with the use of sound for depth measurement, a technique that appears to have been first suggested by the French physicist Arago in 1807. Early attempts were made to measure the ocean depths by detonating from the surface a heavy charge of gunpowder on the bottom of

the sea and determining the interval before the sound was heard (35). This method was successfully used by Behn in measuring the depths of Lake Ploen in 1912. A more sophisticated application of this idea was the British Admiralty depth-sounding machine where a steel hammer striking a steel plate in the bottom of a ship, sent out a highly damped compressional wave, picked up after reflection by a hydrophone. In the "fathometer" of Fessenden, the transmitter was an oscillator sending out a short pulse on a frequency of a few thousand cycles per second. In the years following the First World War the principal maritime countries announced successful trials of echo-sounding equipment, sonic or supersonic.

The *Titanic* disaster had led to Lewis Richardson's proposal that high-frequency supersonic beams could be used for depth measurement and obstacle detection at sea. Such devices became practical after the Langevin and Chilowsky system had produced supersonic beams at 30,000-40,000 cycles per second. Their use of the piezo-electric crystal found an important application in a supersonic pulse device for submarine detection. In World War I development work on these devices went forward in America in the New York and San Pedro groups under the National Research Council. Although it was developed too late to be of use, a supersonic device that could detect submarines half a mile or more away had been built by the end of the war. The Navy continued work on this device. With many improvements, it became the modern *sonar* equipment of World War II. By a simple extension of the basic principle, supersonic altimeters for aircraft were soon thought of.

Between 1920 and 1940 numerous patents were granted and many articles were published on possible methods of using radio for distance measurement. This work had three purposes: (1) point-to-point surveying and geodetic measurements by radio; (2) altimeters for aircraft; (3) exploration of the Kennelly-Heaviside layer. In each the use of pulses was at some time or other proposed.

About 1930 research on finding the distance between two fixed points by radio was undertaken in the Soviet Union. Several different methods were considered including the use of pulses (36). With their final method, a phase displacement method, the Russians in 1934 made a series of 900 measurements in the North Caucasus, shooting between mountain peaks and from peaks to valleys.

Many proposals were made during the first decade after World War I for using reflected radio waves for aircraft altimeters. The patent literature before 1930 yields a wide variety of suggestions for utilizing the reflection of waves directed downward from a plane (37). Of greatest interest, and generally of greatest simplicity, are devices depending on simple measurement of the time required for radiation to travel from a transmitter to a reflecting surface and back. Here several paper patents closely resemble or actually anticipate the pulse method.

The earliest disclosure of this sort appears to be that of an Austrian, Heinrich Löwy, in a patent application filed in July 1923 (38). The patentee describes his proposal as the electric counterpart of Fizeau's method for determining the velocity of light. In Löwy's scheme an electronic switch is used to key a transmitter and synchronously to block and unblock a receiver, so that while the transmitter is sending out a short pulse, the receiver is off; and when the transmitter is silent, the receiver is unblocked and ready to receive the echo signal. The blocking and unblocking are produced by an imposed sinusoidal modulation

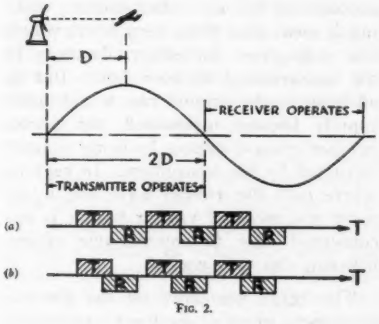


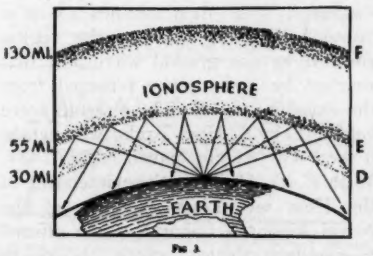
FIG. 2.

the frequency of which can be varied, but which is of the order of broadcast frequencies. In radar parlance, this device has a pulse width roughly equal to the resting time. When the modulation frequency is chosen so that the half wavelength corresponds to twice the distance to the reflecting object, then the situation corresponds to Fig. 2. The reception of the reflected energy begins immediately at the end of the transmission, as in Fig. 2(*a*). When the distance is less than a quarter of the modulation wavelength, the situation corresponds to Fig. 2(*b*) and the returning echo reaches the receiver while the transmitter is still operating. Conversely, when the distance is greater, the received echo returns sometime after the cessation of the transmitter, and continues to arrive after the receiver has been shut off. The output of the receiver is fed to a meter or a gas discharge tube as indicator. Since the maximum signal is received only when the modulation frequency is properly chosen, varying this frequency within convenient limits makes it possible to determine altitude. The essential difference between this pulse device and radar should be evident. In May, 1930, two interesting patent applications were filed by Ezekiel Wolf and by Robert W. Hart and assigned to the Submarine Signal Company of Boston, Mass, (39). Both were for schemes of distance measurement by reflected radio waves, principally for aircraft altimeters, and both provided for the use of pulses of energy. (Wolf's patent applied to continuous waves as well as pulses.)

Hart's patent is for a pulse device corresponding in all essentials to that devised a few years before by Breit and Tuve, which we shall discuss below. Though the language tends to obscure the fact—for example, Hart speaks of "trains of vibration" instead of pulses, and of these trains as being produced by "overmodulation"—his patent is clearly for a pulse-echo altimeter. The pulses from the transmitter are reflected from the ground or other object and the echo is picked up by the receiver and is put on a cathode-ray tube with a circular trace. The cathode-ray trace makes one complete rotation for each cycle of the modulation frequency. The trace can be easily calibrated and the position of the "momentary serration" read as distance to the ground or other target. It differs in no important respect from a nondirectional pulse altimeter.

But the pulse-echo method became best known throughout the scientific world through its use in studying the properties of the *ionosphere*. This is the ionized region of the upper atmosphere of which the lower layer is called the Kennelly-Heaviside layer after the two workers who independently inferred its existence (see Fig. 3).

Marconi's dramatic success, on December 12, 1901, in receiving signals



transmitted across the Atlantic from Cornwall to Newfoundland, led to speculations as to the mechanism which made this possible. Arthur Edwin Kennelly in America and Oliver Heaviside in England independently suggested within a short space of time that these waves were propagated around the curvature of the earth with the assistance of a conducting surface in the upper atmosphere; the waves moving, in Kennelly's words (40), "horizontally outwards in a 50-mile layer between the electrically-reflecting surface of the ocean beneath, and an electrically-reflecting surface, or successive series of surfaces, in the rarified air above."

The suggestions of Kennelly and Heaviside were not accompanied by a serious attempt to explain the formation of the layer. A quantitative theory was offered by Eccles in 1912 based on the assumption that the waves were refracted by the ions in the layer. Although evidence of various kinds began to accumulate in support of the theory of the ionized layer, systematic verification was delayed until interest was once more kindled by the long-distance performance of 100-meter waves, and the discovery of "skip" distance during 1924 (41).

Early in the year John L. Reinartz, one of the best-known radio amateurs, began a series of long-range tests using wavelengths between 20 and 60 meters, and observed that signals which became weaker after sunset (instead of stronger, as with waves about 100 meters) surprisingly enough were audible at great distances. Thus there seemed to be a "dead belt" lying between the region covered by the ground wave and that reached by a sky wave returned from the ionosphere (42). These results were confirmed by A. Hoyt Taylor who named it the "skip" or mis-quoted region (43). With E. O. Hulbert, Superintendent of the Heat and Light Division of the Naval Research Laboratory, he offered a modified Eccles-Larmor theory to account for the new phenomenon, making it clear that these very short waves are propagated for short distances in the conventional manner (44). But in addition to the ground ray, which quite rapidly became attenuated, sky waves reached great distances by being sharply refracted by the ionosphere. In regions where both the ground wave and a sky wave are received violent fading is encountered, due to interference effects between the two waves.

The stage was now set for the experimental proof of the layer's existence. In 1925 Smith-Rose and Barfield in Great Britain applied direction-finding methods on the assumption that there should be a detectable difference in angle between the electric (and magnetic) vectors of the ground and sky waves (45). Their results were inconclusive, though in 1926 they confirmed observations reported in the interim by two other English workers, E. V. Appleton and M. A. F. Barnett (46).

Appleton and Barnett were the first to use reflected radio waves for the radiolocation of a distant surface and the determination of its range (47). Their method was an adaptation of techniques used in Appleton's earlier work on radio signal fading and involved intensity measurements instead of direction-finding methods. They believed that for wavelengths from 300-500 meters there was a point about 100 miles from a given transmitter, where the strength of the ground wave and the sky wave would be sufficiently comparable for strong interference effects to be produced. By varying uniformly the frequency of the transmitter by a known small amount in a brief time—what we now refer to as frequency modulation—it was thought possible to observe directly the interference effects at that point and to determine the distance of the reflecting layer. In experiments performed on the nights of December 11, 1924 and February 17, 1925, using the British Broadcasting Com-

pany's transmitter at Bournemouth, Appleton and Barnett obtained interference effects which were the first direct evidence of the existence of the reflecting layer. They estimated it to be at a height of 80-90 kilometers.

Two American investigators, Merle A. Tuve and Gregory Breit, who undertook an ionospheric investigation without being aware of the similar work going forward in England, were the first to use the simpler radio technique of transmitting discontinuous pulses and measuring the time for the returning echo to reach a nearby receiver.

Their method grew out of one tried at the University of Minnesota by W. F. G. Swann and J. G. Frayne, and, like Löwy's altimeter, used electrical shuttering to block the receiver when the transmitter was sending and unblock it for receiving the echo (48). Breit and Tuve proposed sending out pulses of such a length and repetition rate that at a receiving station some distance away a pulse from the ground wave and the sky wave could be distinguished. From the delay separating the two received pulses, and the known distance between the two stations, the height of the ionosphere could be estimated. The arrangements described in the first paper are shown in Fig. 4 where $A_1$ is the transmitting station, $A_2$ the receiving station, $l$ the distance between the stations, and $h$, the height of the conducting layer.

The general suggestion of studying the reflecting layer by radio was due to Breit. Early in 1924 he proposed to Tuve, then an instructor in physics at Johns Hopkins, that they collaborate in an attempt to transmit radio waves from the Carnegie Institution's Terrestrial Magnetism Laboratory in Washington to Baltimore by reflecting them from the ionosphere. It was Breit's original plan to direct short waves skyward by means of a large parabolic reflector of wire netting, about a 100 feet in diameter, and have the sky

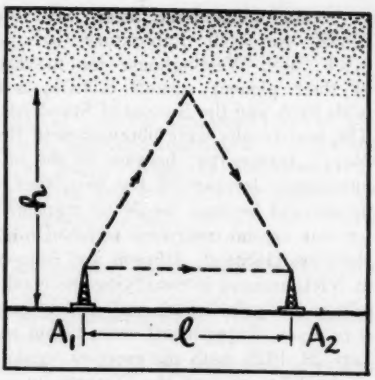



FIG. 4.

wave received by Tuve at Johns Hopkins.

Since the proposal of having the Terrestrial Magnetism Laboratory embark on radio research was something of a novelty, the possibilities were discussed at a meeting, held in November 1924, at which leading radio experts in Washington, like Austin and A. Hoyt Taylor, were called in for consultation. It was during a discussion immediately after this meeting during dinner at Breit's house that Tuve proposed that they try to use pulses in the manner previously suggested by Swann and Frayne at Minnesota. At the close of the spring term in 1929 at Johns Hopkins, Tuve came to Washington and joined his colleague in these historic experiments (49).

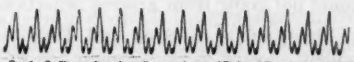


FIG. 5. Oscillogram from the earliest experiments of Breit and Tuve, 3:15 P.M., July 28, 1925, showing ground wave, and double reflections from the Kennelly-Heaviside Layer, using 71 meter transmitter at the Naval Research Laboratory. Pulses produced a.c. modulation on transmitter plate.

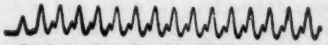


FIG. 6. Early Breit and Tuve oscillogram (September 25, 1925, 3:00 P.M.) showing single reflection from ionosphere and effects of slight fluctuations of the layer.

FIG. 7. Early oscillogram obtained at Carnegie Institution (October 7, 1928) using multivibrator circuit for producing pulses. Note the long interval between successive ground waves (G).

Arrangements were made with the Naval Research Laboratory to use NKF, with Westinghouse for the use of their pioneer station KDKA, and with RCA and the Bureau of Standards. The best results were obtained with the Navy's transmitter, because of the advantageous location of the two laboratories, and because the Navy transmitter was crystal-controlled and had high stability. Gebhard, Schrenk and Young at NRL assisted in modifying the transmitter for pulse work and in building a receiver. Experiments were begun on July 28, 1925, with the receiver located at the laboratory of the Department of Terrestrial Magnetism, 8 miles southeast of the Naval Research Laboratory. Pulses lasting about 1/1000 sec. were transmitted on 71.3 meters. Pulse modulation was produced by an a-c. frequency of about 500 cycles per second applied to the plate circuit of the transmitter. The received pulses, recorded by an oil-immersed General Electric oscillograph, were observed visually by means of a rotating mirror and also photographed. From the time delay, Breit and Tuve estimated the height of the ionosphere as between 50 and 130 miles (50). Additional observations showed that reflections could be obtained using waves of about 40 meters in length, but that no reflections were obtained with waves below 20 meters. The reflections apparently varied with the time of day and with the seasons, which seemed to prove that the echoes could not come from ground reflections.

This method of Breit and Tuve was widely adopted as the simplest and most direct. A world-wide network of investigators was soon busy exploring the upper atmosphere by radio and building up increasingly detailed knowledge of the fine structure of the ionosphere, which was found to consist, not of a single region of ionization as was thought at first, but of two or three layers, depending upon whether it is day or night (51). In 1928 Tuve and Dahl described an improvement suggested somewhat earlier by G. Breit for pulsing the transmitter by a better method than the 500-cycle modulating e.m.f. which had produced pulses very close together, separated by an interval scarcely greater than the pulse length, and had led to difficulty in distinguishing multiple reflections, and to poor resolution for small distances (52). The new method involved the multivibrator circuit of Abraham and Block, later to play an important part in both television and radar, as a basic pulse-forming circuit. With this it was possible to get shorter pulses (one or two ten-thousandths of a second) separated by relatively long intervals (a few hundredths of a second).

The technique was improved also by substituting a cathode-ray tube for the mechanical oscillograph. In 1930 Georg Goubau reported the use of a cathode-ray tube with a circular or elliptical trace, synchronized with the pulse cycle (53). In 1931 Appleton reported simultaneously the adoption of the cathode-ray tube with linear trace as an indicator for ionosphere experiments and the use of a self-pulsing or "squegging" transmitter (54). Except for the frequencies employed, the chosen pulse lengths and intervals between the pulses, and the absence of directive antennas, the apparatus used for ionospheric work by the early 1930's bore considerable resemblance to a radar system. It was the ionospheric investigations, moreover, which spread abroad knowledge of the pulse-echo principle, and reduced the art of radio-location by pulses to the level of daily experience.

Radar was developed by men who were familiar with the ionospheric work. It was a relatively straightforward adaptation for military purposes of a widely-known scientific technique, which explains why this adaptation—the development of radar—took place simultaneously in several different countries.

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(7) Donald R. Griffin and Robert Galambos, "The Sensory Basis of the Obstacle Avoidance by Flying Bats," *Journal of Experimental Zoology,* Vol. 86, pp. 481-506 (1941); Robert Galambos, "The Avoidance of Obstacles by Flying Bats: Spallanzani's Ideas (1794) and Later Theories," *Isis,* Vol. 34, pp. 132-139, (1942). It is established today that the bats avoid obstacles by emitting supersonic notes. A highly developed binaural sense enables them to interpret the echoes correctly and so to locate obstacles in space with great accuracy.

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(10) Augusto Righi, *L'Ottica delle Oscillazioni Elettriche,* Bologna, 1897. Ignaz Klemencic studied the reflection of microwaves from plates made of metal and of sulphur ("Ueber die Reflexion von Strahlen electrischer Kraft an Schwefelund Metal-platten," *Annalen der Physik und Chemie,* Vol. 45, pp. 62-79 (1892)); A. D. Cole working at Berlin successfully applied Fresnel's equations for optical refraction to measurements of the refraction of 5-cm. waves by water and alcohol ("Ueber den Brechungs-exponenten und das Reflexionsvermogen von Wasser und Alkohol für electrische Wellen," *Ibid,* Vol. 57, pp. 290-310 (1896)).

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(16) *QST,* January, 1924, pp. 9-12. For the French account see Leon Deloy: "Première communication transatlantique bilaterale entre postes d'amateurs," *L'Onde Electrique,* Vol. 2, pp. 678-683; see also his "Communications transatlantiques sur ondes de 100 metres," *ibid,* pp. 38-42 (1924).

(17) A. Hoyt Taylor, "The Navy's Work on Short Waves," *QST,* May, 1924, pp. 9-14.

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An attempt was made to place the theory of vacuum tube oscillators at ultra-high frequencies on a sound basis. The study was inaugurated by Denham in 1928 when he explored the effect of electron transit time on the behavior of a diode at moderately high frequencies. Cf. W. E. Benham, "Theory of the Internal Action of Thermionic Systems at Moderately High Frequencies," *Philosophical Magazine*, Part I, Vol. 5, pp. 641-62 (1928) and Part II, Vol. 11, pp. 457-517 (1931). An extension of the Benham treatment to include triodes with a positive or negative grid was made by Llewellyn. Cf. F. B. Llewellyn, "Vacuum Tube Electronics at Ultra-High Frequencies," *loc. cit.*, Vol. 21, pp. 153-73 (1933), also printed in the *Bell System Technical Journal*, Vol. 13, pp. 59-101 (1934). See also his "Note on Vacuum Tube Electronics at Ultra-High Frequencies," *loc. cit.*, Vol. 23, pp. 112-27 (1935), and his "Operation of Ultra-High-Frequency Vacuum Tubes," *Bell System Technical Journal*, Vol. 14, pp. 632-65 (1935). C. J. Bakker and G. De Vries, "On Vacuum Tube Electronics," *Physika*, Vol. 2, pp. 683-97 (1935), advanced a now generally accepted theory of transit time effects within a triode, and confirmed this theory experimentally, showing for the first time a negative resistance caused by finite transit time, at frequencies low compared with the reciprocal of the transit time.

(25) B. J. Thompson and G. M. Rose, "Vacuum Tubes of Small Dimensions for Use at Extremely High Frequencies," *Proceedings of the I.R.E.*, Vol. 21, pp. 1707-21 (1933). See also B. Salzberg, "Design and Use of 'Acorn' Tubes for Ultra-High-Frequencies," *Electronics*, September, 1934, pp. 282-3 and 293; and his "Recent Developments in Miniature Tubes," *loc. cit.*, Vol. 23, pp. 1142-57 (1935).

(26) But see Captain H. B. Jackson, "On some phenomena affecting the transmission of electric waves over the surface of the sea and earth," *Proceedings of the Royal Society*, Vol. 70, pp. 254-72. Jackson first demonstrated the role of the earth in the transmission of radio waves and called attention to the shielding effect of mountains and large land masses.

(27) A. Hoyt Taylor, "The Navy's Work on Short Waves," *QST*, May, 1924, p. 10.

(28) The effect was looked for shortly after by L. D. Grignon, S. M. Hudd and Frank C. Jones who made observations on 3 meters. They did not find it as large as expected. See Frank C. Jones, "Pioneer short-wave work," *QST*, May, 1925, pp. 8-14.

(29) W. J. Brown, "Ultra-short waves for limited range communication," *Proceedings of the I.R.E.*, Vol. 18, pp. 1137-8 (1930); L. F. Jones, *loc. cit.*, Vol. 21, pp. 362-3 (1933); William H. Wenstrom, "Historical Review of Ultra-Shortwave Progress," *loc. cit.*, Vol. 20 (1932).

(30) Carl R. Englund, Arthur B. Crawford, and William W. Mumford, "Some Results of a Study of Ultra-Short-Wave Transmission Phenomena," *Proceedings of the I.R.E.*, Vol. 21, p. 1 (1933).

(31) British Patent No. 13,170, application accepted September 22, 1904. A second application embodying improvements (a "radome" or rotatable housing of wood or some similar substance to protect apparatus from the weather; an impractical method of estimating range by varying the vertical angle of the transmitted beam) was made November 22, 1904 and accepted (British Patent No. 25,608) March 23, 1905.

(32) Senatore Guglielmo Marconi, "Radio Telegraphy," *Proceedings of the I.R.E.*, Vol. 10, p. 237 (1922).

(33) *Naval Personnel*, June 1943, p. 10. A copy of this report is in the Naval Research Laboratory, Anacostia, D. C.

(34) W. J. Brown, "Ultra-short waves for limited range communication," *Proceedings of the I.R.E.*, Vol. 18, p. 1142 (1930).

(35) F. M. Maury, *The Physical Geography of the Sea*, 1855, pp. 200-201. It is worth pointing out that some of the early methods of determining the velocity of sound and light involved the timing of pulses of energy over known distances. In the 17th century Mersenne measured the velocity of sound in air by using a pendulum to time an echo. Likewise Pizeau's measurement of the velocity of light (1849) involved "pulsing" the light by means of a toothed wheel.

(36) The results are summarized in English in *Technical Physics of the USSR*, Vol. IV, 1937.

(37) C. D. Tuska, "Historical Notes on the Determination of Distance by Timed Radio Waves," *Journal Franklin Institute,* Vol. 237, pp. 1-20 and 83-102 (1944). An excellent survey of the problem is to be found in the article by K. Dziewior in *Luftfahrtforschung,* June 1929, pp. 326-388. I am indebted to Mr. E. M. Deloraine of the International Telephone and Telegraph Co. for calling my attention to this article and for putting in my hands an excellent unpublished survey of the literature on distance measurement and obstacle detection: *Note Technique No. 32, Documentation zur la Détection d'Obstacles,* Les Laboratories L.M.T., January 1940.

(38) Löwy, U. S. Patent 1,585,591, filed July 17, 1923.

(39) Wolf, U. S. Patent 1,924,174; Hart, U. S. Patent 1,924,156, both filed May 19, 1930.

(40) The first suggestion of a conducting layer in the upper atmosphere was made by Balfour Stewart in 1878 in his article "Terrestrial Magnetism" in the 9th ed. of the *Encyclopedia Britannica,* to account for cylical variation in the earth's magnetism.

A. E. Kennelly, "On the Elevation of the Electrically-conducting Strata of the Earth's Atmosphere," *Electrical World and Engineers,* Vol. 39, p. 473 (1902). Heaviside's suggestion that a single layer existed was written three months later and published in December 1902 in the article "Telegraph Theory," *Encyclopedia Britannica,* 10th ed., Vol. 33, p. 215.

(41) That reflection from an upper conducting layer was a factor in long distance transmission was indicated by propagation experiments carried out by L. F. Fuller between San Francisco and Honolulu on 3000-11,500 meters. See account of these experiments in *Electrical Review and Western Electrician,* Vol. 66, pp. 736-7 (1915), and comments of Lieut. Com. A. J. Hepburn, *ibid.;* A. Hoyt Taylor, "The Navy's Work on Short-Waves," *QST,* May 1924, pp. 9-14; A. E. Kennelly, "The Conference, in Relation to Amateur Activities," *QST,* December 1924; Sir Joseph Larmor, "Why Wireless Electric Rays Can Bend Round the Earth," *Philosophical Magazine,* Vol. 48, pp. 1025-36 (1924).

(42) John L. Reinartz, "The Reflection of Short Waves," *QST,* April 1925, pp. 9-12. According to R. Jouast ("Some Details Relating to the Propagation of Very Short Waves," *Proceedings of the I.R.E.,* Vol. 19, pp. 479-80 (1931); and "Les ondes très courtes," *L'Onde Electrique* Vol. 9, p. 8 (1930)) the discovery of the skip distance was anticipated in 1921 by Colonel Chaulard of the French Army.

(43) A. Hoyt Taylor, "Investigation of Transmission on the Higher Radio Frequencies," *Proceedings of the I.R.E.,* Vol. 13, pp. 677-683 (1925).

(44) A. H. Taylor and E. O. Hulburt, "The Propagation of Radio Waves," *Physical Review,* Vol. 27, pp. 189-215 (1926).

(45) R. L. Smith-Rose and R. H. Barfield, "On the Determination of the Direction of Forces in Wireless Waves at the Earth's Surface," *Proceedings of the Royal Society,* Series A, Vol. 109, p. 587 (1925), and their "Some Measurements on Wireless Wave Fronts," *The Wireless Engineer,* Vol. II, p. 737 (1925).

(46) R. L. Smith-Rose and R. H. Barfield, "An Investigation of Wireless Waves Arriving from the Upper Atmosphere," *Proceedings of the Royal Society,* Series A, Vol. 110, pp. 580-614 (1926).

(47) Appleton's earliest report is to be found in *Tijds, Nederland Radio-genootschap,* Vol. 2, p. 115 (1925), which I have not consulted. I have used Appleton and Barnett, "On Some Direct Evidence for Downward Atmospheric Reflection of Electric Ray," *Proceedings of the Royal Society,* Series A, Vol. 109, pp. 621-641 (1925), which is the first extended account.

(48) M. A. Tuve and G. Breit, "Note on a Radio Method of Estimating the Height of the Conducting Layer," *Terrestrial Magnetism and Atmospheric Electricity,* Vol. XXX, pp. 15-16 (1925). See also G. Breit and M. A. Tuve in *Nature,* Vol. 116, p. 357 (1925).

(49) Personal communications of Dr. Tuve.

(50) G. Breit and M. A. Tuve, "A Test of the Existence of the Conducting Layer," *Physical Review,* Vol. 28, pp. 554-575 (1926).

(51) A general survey of the progress of ionospheric investigations is found in L. V. Berkner's chapter, "Radio Exploration of the Earth's Outer Atmosphere," in J. A. Fleming *et al., Terrestrial Magnetism and Electricity,* McGraw-Hill, 1939, pp. 434-491; and in H. R. Mimno, "The Physics of the Ionosphere," *Reviews of Modern Physics,* Vol. 9, pp. 1-43 (1937). Some discussion of the various methods used is to be found in Tuska, *loc. cit.*

(52) M. A. Tuve and O. Dahl, "A Transmitter Modulating Device for the Study of the Kennelly-Heaviside Layer by the Echo Method," *Proceedings of the I.R.E.,* Vol. 16, pp. 794-798 (1928).

(53) G. Goubau, "Eine Methode zur Untersuchung von Echos bei des Ausbreitung elektromagnetischer Wellen in der Atmosphere," *Physikalische Zeitschrift,* Vol. 31, pp. 333-4 (1930).

(54) E. V. Appleton and G. Builder, "A Simple Method of Investigating Wireless Echoes of Short Delay," *Nature,* Vol. 127, p. 970 (1931).

## ERRATUM

In the second paragraph on page 874 of the JOURNAL issue of November, 1950 ("Lights and Laws" by Charles E. Wilkenloh), there appears the following statement, ". . . (2) be colored green on the port side and red on the starboard." This should have read, ". . . (2) be colored green on the starboard side and red on the port."

It will be recognized that this is the type of technical error which causes red faces. We refuse to permit the excuse of ignorance but must admit gross editorial carelessness.

# BOOK REVIEW

## THEORY OF THE INTERIOR BALLISTICS OF GUNS

## BY J. CORNER PUBLISHED BY JOHN WILEY & SONS

Reviewed by Dr. C. C. Bramble

Director of Ballistics and Computations Division
Naval Proving Ground, Dahlgren, Virginia

The student of interior ballistics who reads easily only the English language has been for many years at a distinct disadvantage, since very little has been published in English on the subject. Publications in both French and German have been abundant, and a new text on Interior Ballistics was published in Russian in 1949 by M. E. Serebryakov. The best and most comprehensive survey to 1926 was the Innere Ballistik of Cranz. This was not available in English until published by the Office of Scientific Research and Development in a very limited edition in 1945 almost twenty years after its first publication in Germany. Little was done in this country in interior ballistic publication prior to World War II. The textbooks on Ordnance in use by the Navy presented only the Leduc method in their discussion of interior ballistics with the result that the reader had little suggestion from these texts that this was a very small facet of the subject.

The Theory of the Interior Ballistics of Guns by J. Corner goes far to remedy the need for a well considered summary of this field up to the present time. The book reviews the important contributions of the past, since these, whether obsolete or not, serve the important purpose of orienting the student of the subject. The author sets forth methods in several categories which differ in the basic assumptions and mathematical treatment employed. By no means are all developments in each class discussed but at least one of each is presented in detail with British developments naturally predominating.

In much of the discussion in the book the many important contributions are presented in brief statements with references to the original reports given in footnotes. This makes the book easy to read for rapid survey of the field and at the same time a valuable background for a seminar provided students had access to the extensive bibliography thus presented.

The impetus given the study of interior ballistic problems by the War is seen in the inclusion of a number of topics which, to the reviewer's knowledge, have not appeared in English in unrestricted publication. Among these are Similarity relations (Uebertragungs Regeln), Optimum Problems, Leaking Guns (with theory of nozzles), the Smooth Bore Mortar, the Muzzle Brake, the Tapered-Bore Gun, the Maximum possible muzzle velocity and the motion of the propellant in the gun. It is to be regretted that some recent work is still restricted and hence could not be included.

It is the reviewer's opinion that if the author were to rewrite the section on numerical methods at the present moment he would assess the situation differently in the light of the recent developments of high speed digital computers of great flexibility. A considerable volume of recent computation has recently been done in this country and much more will undoubtedly follow.

The Theory of the Interior Ballistics of Guns is written in a style that is concise, but clear, interesting and with some nice turns of expression that make the reader aware of a personality behind the printed page. The mathematical treatment is gentle but sufficient for the author's objectives. More has been covered in fewer pages than in any previous attempt in this subject.

The reviewer is greatly pleased with this book, recommends it to anyone interested in interior ballistics, and congratulates the author on a task splendidly done.

The Society has learned with deep regret of the death of the following since the publication of the November, 1950, Journal:

GEORGE E. BREECE, Civil Member
JAMES BRISCOE, Associate Member
LOGAN CRESAP, Naval Member
P. F. GIBSON, Naval Member
CHESTER M. ROE, Civil Member
NORMAN WALLACE STIRLING, Naval Member
HOLLIS WALTER, Civil Member
J. G. WILSON, Civil Member

## CHANGES IN MEMBERSHIP

It is with great pleasure the announcement is made that the following new members have been admitted since the publication of the November, 1950, JOURNAL:

### NAVAL

Armstrong, Robert T., Lieutenant, U.S.N.R., Sales Engineer,
The Sharples Corp., 2300 Westmoreland St., Philadelphia 20, Pa.

Blanchard, John James, Lieut. Comdr., U.S.N.R., Engineer,
Western Massachusetts Power & Light Co.
Mail: 89 Massasoit St., Northampton, Mass.

Bryant, Eliot H., Vice Admiral, U.S.N., Ret.
Cider Jug Farm, Melvin Road, Route 3, Annapolis, Md.

Campbell, John Francis, Ensign, U.S.N.,
850 Oak St., Lewiston, Me.

Daggett, Rosswell Beldin, Captain, U.S.N., Ret.,
Technical Assistant to President, New York Shipbuilding Corporation,
Camden, N. J.

Feder, Joseph Brown, Commander, U.S.C.G.,
4349 Verplanck Pl., N.W., Washington 16, D. C.

Fichter, Arthur Robert, Lieutenant, j.g., U.S.N.R.,
Govt. Sales, RCA Victor
Mail: Old Marlton Pike, Medford, N. J.

Foster, E. Dorsey, Vice Admiral (SC) U.S.N., Ret.,
% RCA Victor Division, Camden, N. J.

Graham, James Leonard, Lieutenant, j.g., U.S.N.R.,
USS *Manchester* (CL 83), % Fleet P.O., San Francisco, Calif.

Hart, Walter Tillman, Jr., Commander, U.S.N.,
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Leahy, William Harrington, Captain, U.S.N.,
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McShane, Ralph E., Rear Admiral, U.S.N.,
Room 3404, Bureau of Ships, Navy Dept., Washington, D. C.

Mather, Paul Luken, Rear Admiral, U.S.N., Ret.,
Special Assistant to President and Manager,
Precision Equipment Div., DeLaval Separator Co.
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Mroz, Edward J. J., Lieutenant, j.g., U.S.N.R.,
USS *Lenawee*, (APA 195), % Fleet P. O., San Francisco, Calif.

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6604 Exfair Road, Bethesda, Md.

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26741 Midland Road, Bay City, Ohio

Thomsen, Erland David, Ensign, U.S.N.,
USS *Randall* (APA 224), % Fleet P. O., New York, N. Y.

Tweedy, Fred Howard, Lieutenant, U.S.N.,
USS *Ajax* (AR 6), % Fleet P. O., San Francisco, Calif.

Wescot, George Duane, Ensign, U.S.N.R.,
Room 4209 Rogers Hall, U.S.M.M. Academy, Kings Point, N. Y.

## CIVIL

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1001 15th St., N. W., Washington, D. C.

Edmunds, W. Harold, Engineer in Charge Small Air Circuit Breaker Div.,
I.T.E. Circuit Breaker Co.,
19th and Hamilton Sts., Philadelphia 30, Pa.

Grimm, George Arthur, President,
Tampa Repair & Dry Dock Co., Inc., P. O. Box 1277, Tampa, Fla.

Haverstick, S. Alexander, Manager Marine & Aviation Engineering,
Westinghouse Electric Corp., E. Pittsburgh, Pa.

Joyner, Archibald Andrew, Commercial Sales,
RCA, Engineering Products Dept.
Mail: 401 Center St., Haddonfield, N. J.

Lang, Walter Thurston, Manager Service Dept.,
Control Instrument Company, Inc., Brooklyn, N. Y.
Mail: 635 24th St., Brooklyn 9, N. Y.

Lohse, Edward Hull, Development Engineering Dept.,
Control Instruction Co., Brooklyn, N. Y.
Mail: 6127 Gates Ave., Brooklyn 27, N. Y.

McAulay, David B., Bureau of Ships, Navy Dept.,
Mail: 8503 Hempstead Ave., Bethesda, Md.

Mahan, Joseph R., Director of Engineering,
National Supply Co., P. O. Box 899, Toledo 1, Ohio

Meehan, Edward J., Jr., Engineering Aero., RCA,
Mail: 7402 Wildwood Drive, Tacoma Park, Md.

Morris, Marvin N., Application Engineer,
I.T.E. Circuit Breaker Co., 19th and Hamilton Sts., Philadelphia 30, Pa.

Nelson, Roy Evert, Research & Development Work,
Govt. Sales, RCA Victor Division
Mail: 16 Oakridge Road, Bloomfield, N. J.

Palmer, Earl L., Electrical Engineer in Charge Electronics Power Distribution Systems Design for Naval Ships, Bureau of Ships, Navy Dept.,
Mail: 3268 Queenstown Drive, No. 112, Mt. Ranier, Md.

Ryder, Frank Charles, Cataloger of Technical Equipment for U.S. Navy,
Mail: 805 St. Marks Ave., Brooklyn, N. Y.

Travis, Harrison Odell, Jr., Lieut. Commander, U.S.M.S.,
Chief of Marine Engineering, Section, Dept of Engineering,
U.S. Merchant Marine Academy, Kings Point, N. Y.
Mail: 50-37 208th St., Bayside, N. Y.

## ASSOCIATE

Barber, Thomas George, Commander (E), R.N.,
British Joint Services Mission (Navy Staff), Staff
Electrical Officer, Benjamin Franklin Station, Box 165, Washington, D. C.

Blair, Norman, Job Engineer in Charge Piping Stresses Analysis Group,
Bechtel Corp., Power Div., San Francisco, Calif.
Mail: 489 Bayshore Boulevard, Burlingame, Calif.

Burns, Arthur John, Sales Engineer, the Electric Storage Battery Co.,
Mail: Apt. 101, 3368 Chillum Road, Mt. Rainier, Md.

Chambers, George Haddon, Commander (E), R.N.,
Staff Engineer Officer (Propulsion), British Navy Staff,
1910 K St., N. W., Washington, D. C.

Costas, Chrysanthis, Commander (EO), R.H.N.,
Chief, Fuels & Lubricants, Engineering Dept., Ministry of Marine of R.H.N
42 Karneaudou St., Athens, Greece

Collins, Milton S., President, The American Publishing Co.,
1825 K St., N. W., Washington 6, D. C.

Davy, Arthur Cecil Montague, Commander, R.C.N.,
Engineer in Chief, R.C.N.
% Dept. of Defense, Ottawa, Ont., Canada

Familiant, David Gregory, Marine Engineer,
ATID Navigation Co., Ltd., P. O. Box 617, Haife, Israel

Hess, R. Talbor,
10537 Elk Ave., Cleveland 8, Ohio

Paul, James E., Philadelphia District Manager,
The Sharples Corp., 2300 Westmoreland St., Philadelphia, Pa.

Porter, Frederick Meredith, Engineering Dept, and Assistant Secretary,
Electric Tachometer Corp., Philadelphia, Pa.
Mail: Rose Valley, Moylan, Pa.

Rajan, Krshna Tyag, Trichen, Republic of India,
Principal, Institute of Technology

Spencer, Brian Roff, Captain (E), R.C.N.,
Supt. H. M. C. Dockyard, Esquaimalt, B. C.

## THE FOLLOWING HAVE RESIGNED:

NAVAL:

Bohjellan, Albert B.
Boyce, T. C.
Christensen, Robert P.
Colmar, Peter V.
Cooke, George E.
Craig, Edward
Croft, Huber O.
Davis, Rees P.
Dunning, Bruce B.
Griffin, Robert M.
Harpster, David L.
Hawk, Claude V.
Heddell, James V.
Hewitt, John Vance
Kniskern, H. P., Jr.
Lackey, H. B.
Lamons, Ernest W.
Layton, Donald M.
McGuigan, Joseph Lloyd
Menaffey, William C.
Mounger, T. B.
Myerson, Melvourne Z.
Norwood, Gustav
O'Connor, Gustavus
Pennoyer, Frederic W., Jr.
Reed-Hill, Ellis
Sachs, Ben H.
Schlag, Robert Cameron
Smith, Walter May
Zeiger, John G.

CIVIL:

Dalzell, R. C.
Davies, James A.
Grimes, William F.
Rogge, H. H.
Shirley, A. P.
Stine, W. E.
Stull, A. J.
Young, James

ASSOCIATE:

Appel, Arno A.
Batchler, Wm. J.
Cioli, Omer B.
Dossor, Frederick
Ewertz, Eric H.
Hubbard, Howard M.
Rust-Oppenheim, August
Stevenson, George G.
Taylor, Walter F.

DROPPED:

It is with the utmost regret that it is found necessary to report that 296 members have been dropped from membership because of arrearage in dues beyond that permitted by the By-Laws.

# ASSOCIATION NOTES

## ORIGINAL ARTICLES

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscript accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $40.00 to $150.00 depending upon length, interest and professional value.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5. Photographs may be negatives, but glossy prints are acceptable.

6. Include on a separate page a short biographical sketch(es) of the author(s). 50 to 100 words for each author is desired.

Manuscripts should be mailed addressed to:

Secretary-Treasurer
American Society of Naval Engineers
605 F St., N. W.
Washington 4, D. C.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 10 reprint copies of his article free of charge. Additional copies may be purchased from the Society if the request is received 30 days prior to the publication date which is the 25th of the issue month. Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which insufficient material is already on hand.

### SUBJECT MATTER AND AUTHORS

To assist the editor in programming future issues, the help of all members is solicited. To make it easy, the last page in this issue is readily detachable as you will find. This page has blanks for two entries.

*(a)* What subject would you, as a member, like to see covered by an article in the JOURNAL.

and

*(b)* Who do you consider best qualified to prepare such an article authoritatively, and what is his address (if you know).

Any of these forms which are filled in and mailed to the Society will be received with thanks and the editor will follow up to get the suggested articles prepared.

## PHOTOGRAPHS

Photographs of current or historical interest to readers of the JOURNAL are desired. Any which are accepted by the Society will be purchased by the Society at a standard price of $5.00 each. Such purchase *will not* include any copyright by the Society, but the contributor must hold the Society free from any charge of violation of any previous copyright.

## NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

## SOCIETY LAPEL BUTTONS

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine dignified insignia. It is one-half inch in diameter.

The oak leaves and lettering are red on a gold background.

It is available to all members at fifty cents (50c) each.

## LIFE MEMBERSHIPS

Any member may now purchase a life membership under the following rules:

*(a)* Any dues paid for the year in which life membership is purchased will be credited to the cost of the life membership.

*(b)* Life memberships are non-transferable and terminate with the death of the member.

*(c)* No refund will be made on account of death or resignation of a life member.

*(d)* Life membership will vary in cost with the age of the member at his next birthday following application, as follows:

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*(e)* All life memberships paid in shall be protected by a transfer on the books of the Society of Series G, U. S. Government 2½ per cent bonds. Thus a life membership will be established. It will be credited with moneys paid in for life memberships and debited with the regular amount of annual dues for each life member each year.

## LOCAL CHAPTERS

Local Chapters of the American Society of Naval Engineers may now be authorized by the Council. The following rules for recognition of Local Chapters have been adopted by the Council:

*(a)* Twenty or more regular members, Naval or Civilian, may apply for a Charter as a Local Chapter.

*(b)* Each application must be accompanied by a list of members and a copy of local By-laws. The latter must meet the following minimum requirements.

1. All financial dealings of the local Chapter must be independent of the Society and can in no way obligate the Society as a whole. The local chapter shall set up on a non-profit basis. All accounting shall be local.

2. Each active local Chapter shall receive from the Society a grant of $0.50 per year for each naval member, civil member or associate who resides in the local area and who associates himself with the local Chapter. This grant may be used by the local Chapter to defray any necessary expenses, including (a) Letterheads, (b) Notice cards, (c) Postage, (d) Minimum rental allowance, (e) Secretarial service (part time).

3. Any technical papers presented at local chapter meetings, shall be submitted to the Secretary-Treasurer of the Society for consideration for publication in the JOURNAL. Any paper accepted will be paid for at regular rates.

4. Each local chapter shall submit a quarterly report of its activities to the Secretary-Treasurer. These reports must reach Washington, D. C. prior to 15 January, 15 April, 15 July and 15 October. This report shall contain a list of active local members as of the first day of the quarter for the purpose of computing the amount of grant.

5. Associate members of the Society shall be eligible for membership in a Local Chapter, entitled to all the privileges of other members except voting and holding office.

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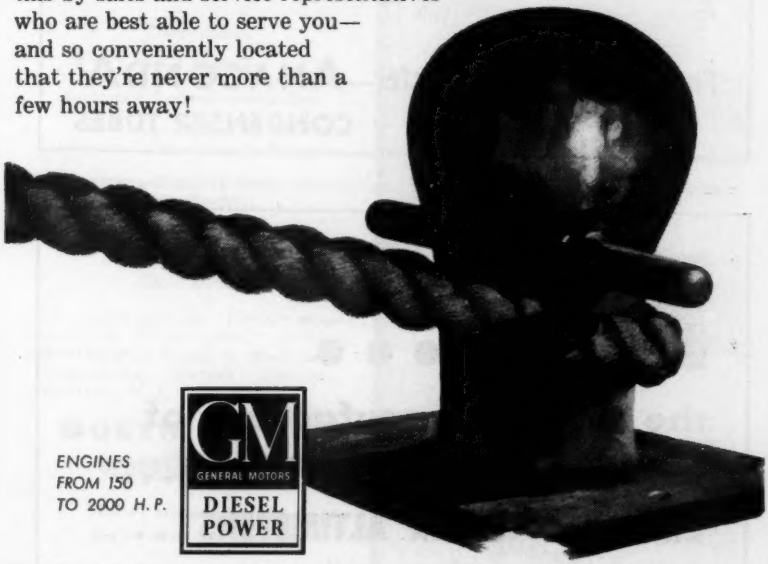

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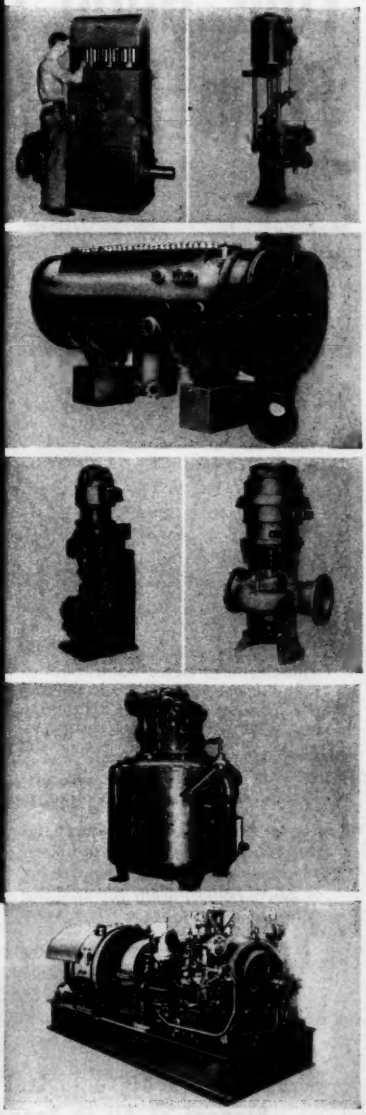

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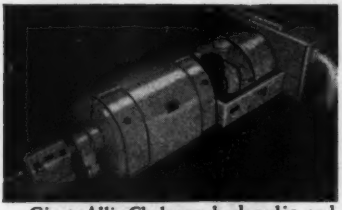

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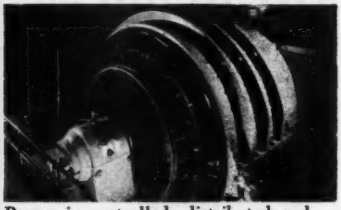

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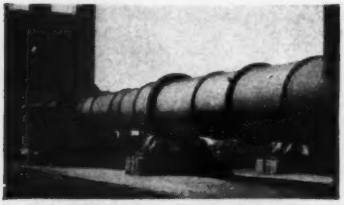

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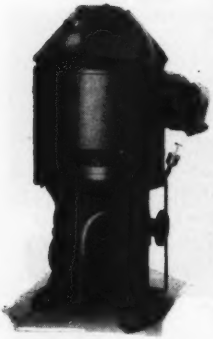

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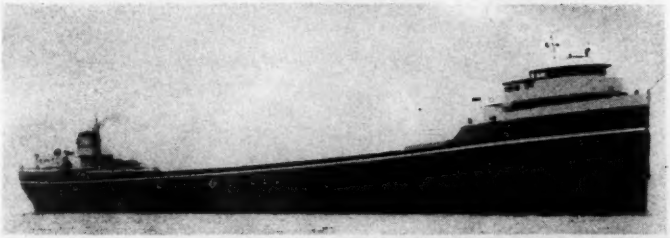

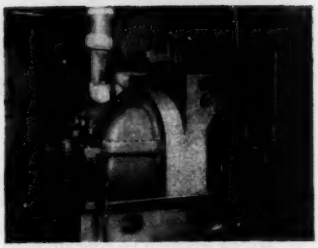

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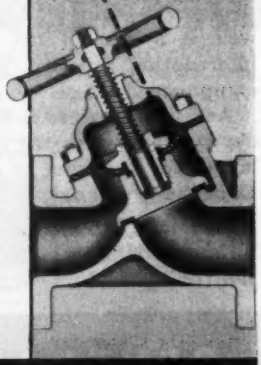

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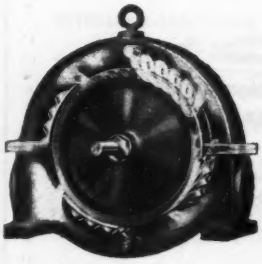

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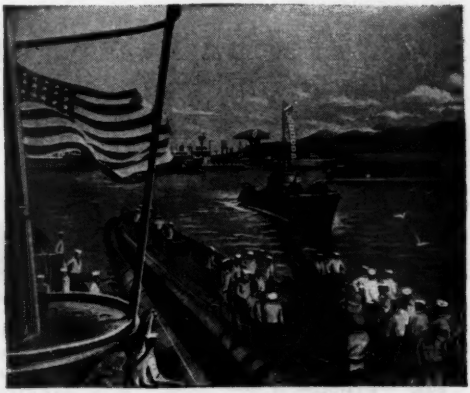

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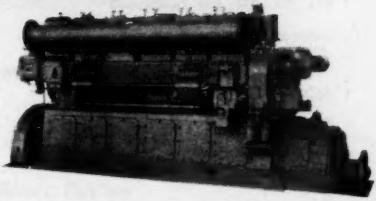

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# Specification Chemicals for the Government and its Contractors

## *Phosphatizing, Rust Proofing and Paint Bonding Chemicals*

| SPECIFICATION NUMBER | ACP SPECIFICATION CHEMICAL |
|---|---|
| QQ-P-416 | "Lithoform," "Zinodine" |
| RR-C-82 | "Lithoform" No. 32 |
| MIL-C-5541 (See also QPL-5541-1) | "Alodine" |
| MIL-S-5002 | "Alodine," "Granodine" (Dip, Spray and Brush grades) |
| JAN-C-490, Grade I | "Granodine" (Dip, Spray and Brush grades) |
| JAN-F-495 | "Granodine" (Dip, Spray and Brush grades), "Lithoform" |
| JAN-L-548 | "Permadine" |
| AN-E-19 | "Alodine," "Zinodine" |
| AN-F-20 | "Alodine," "Granodine" (Dip, Spray and Brush grades), "Lithoform," "Permadine," "Thermoil-Granodine," "Zinodine," (See also U.S.A. 3-213) |
| U.S.A. 57-0-2 | |
| Type Ii, Class A | "Thermoil-Granodine" |
| Type II, Class B | "Permadine" |
| Type II, Class C | "Granodine" (Dip, Spray and Brush grades) |
| U.S.A. 51-70-1 | |
| Finish 22.02, Class A | "Thermoil-Granodine" |
| Finish 22.02, Class B | "Permadine" |
| Finish 22.02, Class C | "Granodine" (Dip, Spray and Brush grades) |
| U.S.A. 50-60-1 | "Granodine" (Dip, Spray and Brush grades) |
| U.S. Navord O.S.675 | "Alodine" |
| U.S.N. Appendix 6 | "Lithoform" |
| Navy Aeronautical M-364 | "Permadine," "Thermoil-Granodine" |
| AN-C 170 | (See MIL-C-5541) |
| U.S.A. 72 53 | (See AN-F-20) |
| AXS-1245 | (See JAN-C-490) |

## *Rust Removing and Metal Conditioning Chemicals*

| SPECIFICATION NUMBER | ACP SPECIFICATION CHEMICAL |
|---|---|
| JAN-C-490, Grade II | |
| Type 4 | "Deoxidine" Nos. 126, 512, 526, 624, 670 |
| Type 5 | "Deoxidine" Nos. 170, 171, 670 |
| U.S.A. 3-213 | |
| Type I | "Deoxidine" (Wash-off grades) |
| Type II | "Deoxidine" (Wipe-off grades) |

## *Metal Cleaning Chemicals*

| SPECIFICATION NUMBER | ACP SPECIFICATION CHEMICAL |
|---|---|
| JAN-C-490, Grade II | |
| Type 2 | "Ridoline" |
| Type 6 | "Ridosol" |
| U.S.A. 3-192 | "Ridoline" No. 3192 |
| U.S.N. Appendix 6 | "Deoxidine" |

## *Acid Inhibitors, Pickling*

| SPECIFICATION NUMBER | ACP SPECIFICATION CHEMICAL |
|---|---|
| U.S.N. 51-1-2 | "Rodine" |

*Write us for descriptive folders and further information on the specification chemicals listed above. Additional copies of this chart are available on request.*

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*Signature of Applicant*

Address for Journal and Mail

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*See reverse side for required qualifications for various classes of membership

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